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DETERMINING THE PREVALENCE OF CERTAIN CEREAL CROP DISEASES BY MEANS OF AERIAL PHOTOGRAPHY¹

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INTRODUCTION

The work reported in this paper was performed under sponsorship of the National Research Council's Committee on Plant and Crop Ecology, Division of Biology and Agriculture.

The specific objectives of the research were: (1) to determine the photographic scale, film, filter, angle, time of day, season of year, and other aerial photographic specifications necessary for detecting and identifying certain important diseases to be found on oats, wheat, barley, and rye; and (2) to determine the recognition features by which these crops and their diseases might be identified on aerial photographs taken to specifications.

In assessing the potential importance of this research the following five facts should be considered:

(1) *The problem of satisfying the world's food requirements is rapidly becoming critical.* A recent report from the United Nations (Stakman, 1955a)³ states that there are 32 million more human mouths to feed every year. By the year 2000 there will be more than 3½ billion humans in the world in contrast to the present 2½ billion. Even now, according to the report, food production is inadequate on a world-wide basis, since two thirds of the people in the world are going hungry.

(2) *Most of the world's food energy comes directly or indirectly from cereal crops.* According to Pearson and Harper (1945), "Grains make up 82.4% of the world's food production and 73% of the food consumed by man. . . . Wheat ranks first or second in importance in each of the 6 continents." Stakman (1955b) states that "for 97% of the people in the world cereal grains constitute the main source of food energy."

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³ See "Literature Cited" for citations referred to in the text by author and date.

(3) *A high incidence of rust or other disease greatly reduces the yield of our most important cereal crops.* In one recent year, approximately 75 per cent of all the durum wheat grown in North and South Dakota was killed by rust, resulting in acute shortages. In the same year, approximately 35 per cent of the bread wheat in the upper Mississippi Valley also was destroyed. Heavy reductions in yield have also been reported for other areas (Suneson and Briggs, 1941; Suneson, 1954). In the experiments on oats and wheat reported herein, disease-induced yield reductions of as much as 70 to 80 per cent were quite common.

(4) *Means for reducing the losses can often be successfully employed if the diseased areas can be detected early and mapped accurately.* As pointed out by Stevens and Stevens (1952), "... a forecast of disease losses is implicit in every attempt at disease control and in every recommendation for disease control." Although complete control of a cereal crop disease, once detected, ordinarily would not be practicable, measures designed merely to retard the rate of spread of the disease from detected infection centers might greatly reduce losses. Thus, there is relatively little reduction in the yield of wheat if the crop can be brought to maturity one week before black stem rust reaches maximum severity. In contrast, yield reductions ordinarily are very heavy when black stem rust reaches maximum severity three weeks before the crop is mature.

(5) *Up to the present time, no means has been available for mapping the extent and severity of these diseases over large areas rapidly, accurately, and economically.* The research herein reported indicates that, under certain conditions, aerial photography can provide such a means.

In the past few decades, great progress has been made in the genetic development of disease resistance in various plants, and perhaps most notably in cereal crops (Stakman, 1955c). Consequently, it might seem that we are on the verge of eliminating cereal crop diseases and therewith the need for disease inventory. That this is not so is evident from the following comments by Stakman (1953): "Let us take rust resistant wheats, for example, rust resistant oats and disease resistant barleys. [The diseases which attack these plants] are not only menacing us all the time, they are causing terrific losses. . . . If we were to bring into the United States a certain strain of rust which occurs in certain countries of the world we would be completely helpless as far as we know, because there are no varieties that are known that are completely resistant. The same is true of many other pathogens. The presence of any new and highly virulent race of rust demands setting up elaborate breeding programs requiring years of research and field trials before any resistant strain can be incorporated in our economy."

Even when a resistant strain has been developed there is no assurance that it will long remain resistant. For about 12 years, several varieties of wheat in the upper Mississippi Valley were resistant to rust. In 1950, that type of resistance disappeared. A similar misfortune suddenly befell the resistant strains of wheat commonly grown in Mexico. In some cases, such an occurrence may be due to the introduction of strains of the pathogen to which local crops are not resistant. In other cases, locally occurring strains of the pathogen are able to develop adaptive mutations at a rate more rapid

than that at which the plant breeder can develop resistance in the host. For example, despite the fact that, in 1953, farmers in the Plains states planted the best varieties of oats that geneticists had been able to develop in 30 years of breeding for rust resistance, oats rust caused more severe yield reductions that year than at any previous time in history.

As Stakman (1955a) has pointed out, if nature can put virulence into pathogens faster than man can put resistance into crop plants, it may soon become necessary to use fungicides on extensive acreages of basic food crops that are subject to widespread epidemics. In such an event, aerial photography flown to the proper specifications should be very useful in selecting the areas wherein fungicides might most profitably be applied.

Recently, much has been said in this country about the grain storage problems and grain price-support problems resulting from our tremendous overproduction of cereal crops. With nearly 2 billion people in the world going hungry today, the problems appear to be those of geopolitics and food distribution, rather than overproduction of cereal crops. Rarely have we had in storage more than a single year's production of grain. In view of the sobering facts just presented, it is evident that our year-to-year production of grain is by no means a certainty, and that our apparent surplus cannot be considered excessive. The extensive support given by many agencies to the research reported herein is indicative of our nation's concern that cereal crop diseases in this country might at any time convert our grain surpluses into severe shortages.

POTENTIAL APPLICATIONS OF THE TECHNIQUES

Certain basic techniques developed in this project are applicable to a wide variety of problems. One example is the technique of using spectral analyses to predict the correct film-filter combination for obtaining recognizable tone or color differences between an object and its surroundings. The writer has since found this technique effective in obtaining aerial photographs suitable for distinguishing soil types, mineral types, plant species, water depths, and "high risk" timber stands in which attacks by insects or diseases are soon likely to reach epiphytotic proportions. Conversely, in those instances where simple, rapid spectral analyses have indicated that no film-filter combination would enable the photo interpreter to make the desired distinction, no usable combination has been found despite extensive aerial photographic tests.

Another broadly useful technique, described here for the first time, is that of using helicopters and fixed-wing aircraft to obtain complementary oblique and vertical photographs.

Several leading agronomists, pathologists, and agricultural economists have reviewed the techniques presented in this paper and have suggested ways in which such techniques might be used in the control of crop diseases.

Stakman (1956) has stated that under certain conditions the early detection of wheat rust infection centers by means of aerial photographs would be helpful in effecting direct control of the disease. Merely making two or three hand-duster applications of sulfur to such infection centers and their immediate environs could provide effective and economical control under

certain situations, provided those centers were detected, on aerial photographs, while still quite small. Stakman emphasizes that such measures would not eliminate the rust, but would merely retard its rate of spread so that most of the plants in a large field could mature before rust had hit them severely enough to reduce their yield appreciably. He also emphasizes that this technique would be most applicable in relatively isolated wheat-producing regions such as are found in parts of California and the Pacific Northwest. In the Central Plains states, such control measures might be quite ineffective because the large wintering grounds for rust in Mexico and Texas provide an almost limitless source of infection, the spores being blown steadily northward by prevailing winds during the growing season.

Investigations currently being conducted by the writer on orchard, timber, and truck crops indicate that certain diseases infesting these crops can also be readily detected at an early date by means of aerial photographs taken with the correct film and filter. Such crops have an even higher value per acre than do cereals, and therefore justify a higher expenditure per acre for disease control.

Several experts on crop diseases believe that the use of aerial photographs will be valuable *indirectly* in helping to develop more effective control measures over a period of several years. Aerial photographs would be used to provide accurate information each year on rates of spread of the diseases and on the localities most heavily hit. When combined with accurate data on spore distribution patterns (Colwell, 1951), this information would constitute the basis for more intelligent control in subsequent years through a better understanding of disease behavior. For example, one agronomist who has been studying the spread of wheat rust in relation to "spore showers" believes that aerial photographs would enable him to pinpoint accurately the spots in which such showers have only recently taken place, even in very large wheat fields which he cannot examine thoroughly and frequently by conventional ground methods. He believes that such timely information would lead to a much better understanding of the meteorological factors contributing to spore showers.

Agricultural economists have expressed their interest in using this aerial photographic technique for making more accurate predictions of crop yields at various critical times during the growing season, thereby facilitating efforts at crop price stabilization.

Research agronomists have evinced considerable interest in this use of aerial photographs as the most effective means of recording and portraying the results of their nursery plot studies on crop diseases.

AN EARLY EXPERIMENT WITH PHOTO INTERPRETATION

A survey of the literature has revealed only one previous attempt to make a disease survey in an agricultural crop by means of aerial photography. This attempt, involving cotton root rot, was performed nearly 30 years ago and was a highly commendable pioneering effort. The results were reported in two brief notes by Neblette (1927, 1928) and in a short paper by Tauben-

haus, Ezekiel, and Neblette (1929). The aerial photographs were taken from very low altitudes (250 to 400 feet), with panchromatic film and a K-1 (light yellow) filter. The investigators concluded that "airplane photos have solved the problem by furnishing views which include entire fields and at the same time differentiate plants killed by root rot from normal plants."

Judging from the four oblique photographs published by these investigators, it does not appear that *plants* killed by root rot were differentiated from normal *plants*. The photographs indicate, rather, that these workers distinguished individual *areas*, in which the diseased plants had already wilted and died (thus exposing the light-toned soil), from adjacent *areas*, in which the dark-toned, healthy plants still formed a continuous ground-cover. Such a conclusion is further indicated by the following statement: "The disease causes definite dead areas or spots in the fields. These spots stand out prominently and are conspicuous even from considerable distances as when viewed from moving trains... or by pilots flying at altitudes as high as 16,000 feet." Inability to detect the disease on a plant-by-plant basis would not seriously deter use of aerial photography for the specific purposes advocated by these investigators, that is, "in estimating losses from cotton root rot, and in furnishing better pictures of the results of field experiments with root rot." However, such inability may explain why these workers did not advocate photography as an aid in the early detection and possible control of the disease. Had this seemed possible, it would no doubt have been advocated since, in the words of the investigators, "cotton root rot, caused by *Phymatotrichum omnivorum* (Shear) Duggar, is one of the most serious plant diseases of the southwest and entails annual losses running into millions of dollars."

RESEARCH METHODS

Basic Considerations

In approaching the problems of identifying and determining the prevalence of cereal crop diseases by means of aerial photographs, it was recognized that the photo identification of cereal crops in the *healthy* state would be a very helpful clue, and in some cases would constitute an essential first step. Accordingly, one part of this investigation was designed to determine whether it is possible for the photo interpreter to identify various cereal crops in the healthy state, while another part dealt with the photo interpretation of these same crops in the diseased state.

As early as 1890, spectrophotometric data were published for healthy leaves, showing their high reflectance of green and infrared light and their strong absorption of blue and red light. By 1936, literature on spectral reflectance, absorption, and transmission by vegetation had become sufficiently extensive to merit an excellent review by Popp and Brown. In the past 25 years, many *terrestrial* photographs of diseased and healthy plants have been taken with a variety of films and filters. However, virtually all of these attempts have been quite empirical in nature, having made no use of spectral analyses for selecting the most suitable film and filter.

Bawden (1933) found infrared terrestrial photography superior to panchromatic for detecting those portions of a potato leaf infested with virus disease. When infrared film was used, the necrosis appeared as dark streaks on positive prints. In photographing the necrosis produced in tobacco by the "X" virus, however, Bawden obtained completely opposite results. The tone contrasts between diseased and healthy areas appeared much more conspicuous on panchromatic than on infrared photographs. In the case of cucumbers affected by fungus, Babel (1935) found that a normal panchromatic photo rendered the general appearance of the diseased flecks more clearly than did an infrared photo. However, the infrared photos showed a dark tone in areas of the leaf which were peripheral to the diseased flecks and in which cellular changes caused by the fungus were taking place. Van Atta (1936), using only panchromatic film, determined which filters would provide the best photographic tone contrast between diseased and healthy tissue in a variety of plants. In general, greatest success was obtained by using a deep red filter, such as the Wratten 70 or Zeiss RG5. The diseased areas then appeared darker in tone than the healthy areas, much as they would on infrared photography. Eggert (1935) photographed the leaves of fruit trees which had been damaged either by spraying or by drought. He found that the damaged parts of the leaves showed up very clearly on infrared but not on panchromatic photos. Clark (1946), in his discussion of the applications of photography to plant pathology, clearly recognizes the importance of spectral analyses in the photographing of plant diseases although he apparently has had no occasion to take such photographs either from the air or on the ground.

Methods used by ground observers for identifying cereal crops and their diseases ordinarily cannot be employed by the aerial photo interpreter. Insufficient clarity of the aerial photographic image obviously makes it impossible for the aerial photo interpreter to identify most cereal crops from their flower characteristics, for example, or to identify a particular cereal crop disease from the appearance of the individual pustules or sori produced by the pathogen on a host plant. In short, the macroscopic characteristics, or mass effects, of an entire stand of grain would have to be relied upon by the photo interpreter, rather than the near-microscopic features of an individual plant or plant part.

Previous work bearing on the problem of crop identification from aerial photographs has been performed by the writer, some of it in collaboration (United States Geological Survey, 1944*a, b*; United States Navy, 1945; Colwell, 1946, 1948), and by others (Kohn, 1952 *et seq.*; Office of Naval Research, 1950). Most of this work was quite broad in scope, and dealt with the photo identification of only the major vegetation types in various parts of the world. It pointed out the means for distinguishing cultivated from wild vegetation, however, and listed the few macroscopic characteristics which might be used in attempting to identify certain cereal crops on conventional aerial photographs. (For example, paddies with levees built along a contour usually indicate rice; wide row spacing, tall, mature stands, and steep-sloped shocks at harvest time usually indicate corn, *et cetera.*) Relatively little information existed, however, which would help the photo interpreter to distinguish

among such important crops as oats, wheat, barley, and rye (Kohn, 1952). Unless some consistently identifiable tone or color difference could be associated with these last-mentioned crops, it would not seem possible to distinguish one from another on aerial photographs. Similarly, it was recognized that perhaps the only hope for distinguishing one type of cereal crop *disease* from others would be through the exploitation of some unique tone or color values, discernible on aerial photographs of the crop, which might be associated with the disease. A preliminary study was made to determine the appearance of various grain fields on existing aerial photographs which had been taken, as usual, with panchromatic film and a minus-blue (haze-cutting) filter. It soon became apparent that such photography offered very little opportunity for the photo identification of cereal crops and their diseases. Since it was not known whether some other combination of film and filter might provide the desired tone differences, investigation of this possibility constituted a major aspect of the research herein reported.

Because of the large number of film-filter combinations that might be employed, it was considered economically impracticable to make aerial photographic tests with each possible combination. A large number of such tests, involving several kinds of objects and several film-filter combinations, had previously been performed more or less empirically (Ryker, 1933; Clark, 1946; Jensen and Colwell, 1949; Shulte, 1951). Ives (1939), in investigating the use of infrared photography for ecological surveys, had found that healthy grasses and cacti are among the best reflectors of infrared light, while mature and drying grasses and unhealthy cacti are poor infrared reflectors. The present writer had expressed the view (American Society of Photogrammetry, 1952) that it should be possible to predict, for any particular film-filter combination, the aerial photographic tone or color of an object provided the following factors were known: (1) spectral reflectance of the object being photographed; (2) spectral sensitivity of the photographic film; (3) spectral scattering by atmospheric haze; and (4) spectral transmission by the photographic filter.

It was, of course, recognized that several other factors, such as amount of exposure, nature of the light source, and laboratory techniques and materials used in processing and printing, likewise exert important influences on photographic tone and color. When these additional factors are in suitable balance, however, as is usually the case, the four factors listed above were believed to be the critical ones governing photographic tone and color. If this theory were correct, then it seemed that a systematic analysis of the four major factors with reference to the problem at hand should rule out most of the film-filter combinations which might otherwise be tried strictly on a trial-and-error basis. At the same time, such an analysis should indicate those few film-filter combinations offering greatest promise for making the desired photo identifications. As will presently be shown, the close agreement obtained between predicted and actual photographic tones and colors, when the above type of analysis was employed, speaks well for the efficacy of the method, not only for this problem, but also for many related photo interpretation problems.

The following discussion relates the four major factors governing photo-

graphic tone and color to the aerial photo identification of healthy and diseased cereal crops.

(1) Spectral Reflectance of the Cereal Crop. At present no spectrophotometer is available which will give reflectance data directly for an entire stand of grain or even for an entire plant. Instead, it is necessary to mount a small specimen, for which light reflectance data are desired, between two glass plates which are then placed in front of the spectrophotometer's circular window. (See figs. 1 and 3B.) The question therefore arose as to which portion of the grain plant (stems, leaves, or inflorescences) should be used in order to obtain reflectance data that would be the most meaningful for predicting aerial photographic tone or color values of a grain field. It was recognized that vertical aerial photography (taken with the camera axis pointed vertically downward) rather than oblique photography ordinarily would be employed. Preliminary tests showed that it is the upper leaves, more than any other part of the plant, which are exposed most directly in vertical photography and which will therefore govern in large measure the plant's photographic tone or color. (See fig. 3.) Accordingly, in most cases where oblique aerial photography was not contemplated, reflectance data were obtained only for the plant's upper leaves.

It was considered desirable to determine light reflectance not only in the

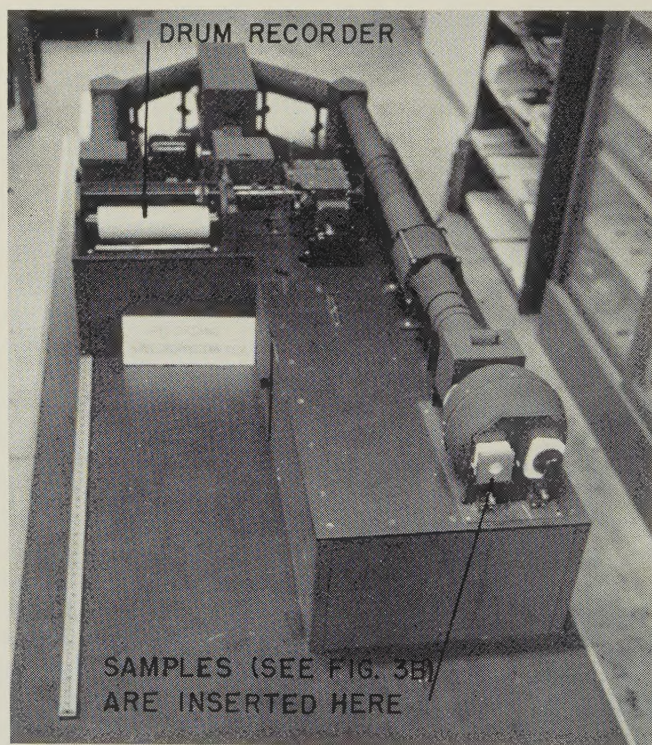


Fig. 1. General Electric Recording Spectrophotometer used for the measurement of spectral reflectance of healthy and diseased cereal crops.

visible part of the spectrum, but also in the infrared part. Light reflectance in the ultraviolet part of the spectrum was not considered worthy of investigation since it was recognized that, even though reflectance differences might be found there, it would be virtually impossible to exploit them on aerial photography for reasons indicated in (3), below.

(2) Spectral Sensitivity of the Film. Preliminary analyses of various diseased and healthy cereal crops showed that, at the most, four films would be needed to exploit those parts of the spectrum in which photographic tone or color differences might most logically be found among cereal crops. Two were black-and-white films (Super XX Aero Panchromatic and Infrared Aero), and two were color films (Kodak Ektachrome Aero film (high contrast), commonly known as "aerial ektachrome," and Kodak Camouflage-Detection film).

(3) Spectral Scattering by Atmospheric Haze. Rayleigh's law states that the intensity of scattered light varies inversely as the fourth power of the wave length. Results obtained in actual aerial photographic tests by von Kujawa and others, as reported by Clark (1946), are in essential agreement with the law, but results obtained by Coleman (1948), Duntley (1946; 1948a; 1948b), Hurlbert and Tousey (1948; 1949), and Middleton (1950) are in only approximate agreement. Consistent with the law, all these investigators found that haze interference is a far more serious problem to the aerial photographer when exposing for short wave lengths of light than when exposing for long ones. In relation to the problem herein reported, this simply means that light reflectance differences occurring among cereal crops in the ultraviolet and blue portions of the spectrum would be much more difficult to exploit photographically than would those differences found in the red or infrared parts.

(4) Spectral Transmission by the Photographic Filter. Of the several hundred filters which might have been employed in this research, only two were considered necessary in view of preliminary reflectance data obtained for cereal crops. These are the Wratten 25A filter, which transmits only visible light in the red end of the spectrum, and the Wratten 89A filter, which transmits only near-infrared light. (Strictly speaking, since infrared radiations cannot be seen, they should not be referred to as "infrared light." Perhaps even the term "infrared photography" is incorrect. However, infrared-sensitive films serve to make infrared radiations visible, and consequently these radiations are commonly referred to as "infrared light.") In addition to the two filters mentioned above, a Wratten 12 (minus blue) filter was used in some of the tests to determine the extent to which conventional "panchromatic minus blue" photography would permit the desired photo identifications to be made.

When taking *black-and-white photographs*, the photographer must recognize the limitations imposed by factors (1) and (3), both of which are essentially beyond his control. He must then arrive at a combination of the other two factors (film and filter) which will produce suitable tone characteristics. The succeeding portions of this report show how this frequently can be done for cereal crops in a direct manner rather than on a trial-and-error basis.

In *color photography*, still another of the four factors passes largely out of the control of the photographer, namely, the photographic filter to be used. If the filter gives more than a slight color-correction, the resulting photographic images will exhibit decidedly abnormal color characteristics. It is true that, in the case of camouflage-detection film, abnormal photographic color characteristics are acceptable or perhaps even preferred, but for most purposes of this study, the value of the color photography was considered to be directly proportional to the faithfulness with which it registered various colors as they normally should appear on that particular film. It was this consideration that severely limited the choice of filter when taking color photography.

1952 Tests on Rusted Wheat

During the spring and summer growing season of 1952, preliminary tests were made, under the writer's direction, on several varieties of wheat grown in test areas at Stillwater, Oklahoma, and at Langdon, North Dakota.

The test area at Stillwater was of the "open field" type, consisting of a strip 20 miles long and $\frac{1}{2}$ mile wide. This area was selected by Professor Harry C. Young, Department of Plant Pathology, Oklahoma Agricultural and Mechanical College, after extensive visual reconnaissance from both ground and air. The pathogen was *Puccinia triticina*, which causes leaf rust of wheat.

The test area at Langdon was of the "nursery" type, consisting of small, well-controlled plots with five rows of wheat per plot. The pathogen was *Puccinia graminis tritici*, which causes black stem rust of wheat. Each plot contained a particular hybrid having a relatively uniform stem rust susceptibility which differed from that in adjacent plots. Rust incidence ranged from about 5 per cent in some plots to 80 per cent in others. This area was included in the tests on recommendation of Dr. H. A. Rodenhiser, Head of the Division of Cereal Crops and Diseases, U.S. Department of Agriculture.

From the Stillwater locality, representative plants were selected for spectral reflectance measurements. The plants were harvested at various stages of development, and carefully wrapped in moisture-proof paper. A ball of moist soil was left intact around the roots as a further deterrent to wilting. The plants were flown to Washington, D.C., on the same day that they were harvested, and were promptly subjected to spectral reflectance measurement by Mr. John C. Schleter in the Photometry and Colorimetry Section of the National Bureau of Standards. A photoelectric recording G. E. Spectrophotometer was used for the analyses. Separate measurements were made of leaves, stems, and inflorescences. Similar measurements were made on plants grown at the Plant Industry Station of the United States Department of Agriculture in Beltsville, Maryland. Since this station is less than 20 miles from the National Bureau of Standards, it was possible to retain maximum freshness of the collected specimens up to the time that they were analyzed in the spectrophotometer.

Reflectance curves obtained on plants grown at the above localities (Keegan, *et al.*, 1956) indicated that, within the visible red and near-infrared portions of the spectrum, there were significant differences in the reflectance

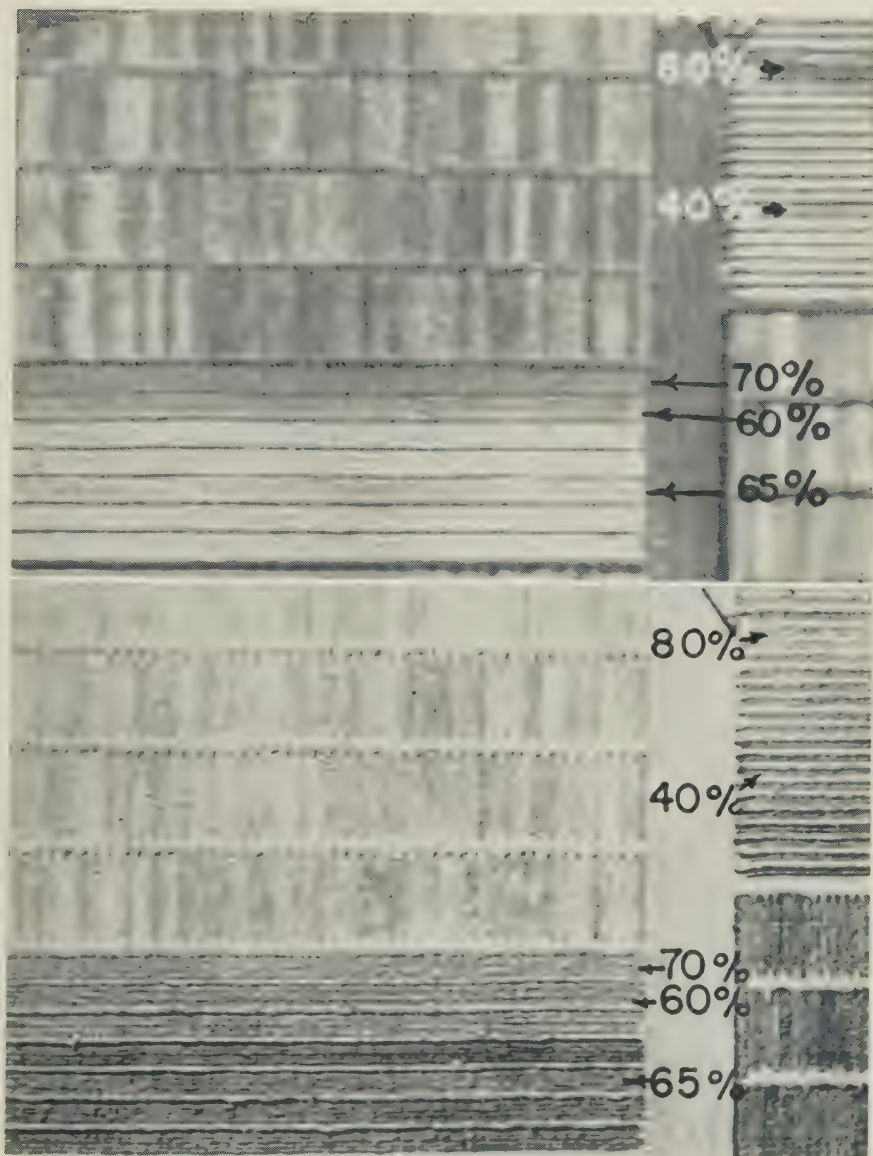


Fig. 2. Infrared-89A (top) and panchromatic-minus blue aerial photographs of healthy and rust-infested plots of wheat growing in the nursery at Langdon, North Dakota. Flight altitude, 2,000 feet. Figures indicate per cent of leaf and stem area covered by pustules of the pathogen, *Puccinia graminis tritici*. All horizontal rows except those labeled are healthy. Note that on the infrared photography all diseased rows tend to appear dark in tone, and all healthy rows, light. On the panchromatic photography, however, no such correlation exists.

of diseased and healthy *leaves*, but only minor differences in the reflectance of diseased and healthy *stems* and *inflorescences*. There appeared to be no significant change in reflectance attributable to loss in freshness of plants during their transport from Stillwater to Washington, D.C.

In an effort to translate these differences in light reflectance of leaves to detectable differences in photographic tone or color, the test areas were subjected to aerial photography on the dates shown below, when rust severity neared the maximum on susceptible varieties, but before the normal green color of any of the varieties started to fade with the onset of maturity.

FILM-FILTER-SCALE COMBINATIONS USED IN AERIAL PHOTOGRAPHY AT
STILLWATER, OKLAHOMA, MAY 15, 1952

1. Panchromatic film, Wratten 25A (light red) filter, scales 1/2000 and 1/4000.
2. Panchromatic film, Wratten 12 (minus blue) filter, scale 1/2000.
3. Infrared film, Wratten 89A (dark red) filter, scale 1/2000.
4. Ektachrome (color) film, color-correction filter, scale 1/400.

FILM-FILTER-SCALE COMBINATIONS USED IN AERIAL PHOTOGRAPHY AT
LANGDON, NORTH DAKOTA, AUGUST 14, 1952

1. Panchromatic film, Wratten 12 (minus blue) filter, scales 1/800 and 1/2000.
2. Panchromatic film, Wratten 25A (light red) filter, scales 1/800 and 1/2000.
3. Infrared film, Wratten 89A (dark red) filter, scales 1/800 and 1/2000.
4. Ektachrome (color) film, color-correction filter, scales 1/800 and 1/2000.

NOTE: Since all aerial photography shown herein was taken with a 12-inch focal length camera (scale = focal length/flight altitude), flight altitude, in feet, is reciprocal of photo scale.

Photos of the Stillwater area were taken by personnel based at the United States Naval Air Station, Jacksonville, Florida; those of the Langdon area by personnel based at the Naval Air Station, Anacostia, D.C.

The aerial photographs were interpreted at the United States Naval Photo Interpretation Center, where the writer was then in charge of research. In accordance with predictions based on spectrophotometric curves, tone differences between diseased and healthy plants, in these preliminary tests, appeared to be detectable on infrared and color photographs, whereas they were not detectable on conventional panchromatic photographs (fig. 2). Also consistent with predictions, photographic tone or color was the only interpretable characteristic even on the very large scale aerial photographs. No further details relative to these preliminary experiments are presented here. The brief reports in which they were summarized (United States Navy, 1953; Truesdell, 1953) stated the need for additional, and more carefully controlled tests before definite conclusions could be reached.

In 1953 and 1954, the following research was conducted by the writer on test plots at the University of California's Davis campus, in coöperation with Mr. Coit A. Suneson, Research Agronomist of the U.S. Department of Agriculture, assigned to the University's Department of Agronomy.

1953 Open Field Tests on Healthy Oats, Wheat, and Barley

As illustrated in figure 3C, an 80-acre block on the Davis campus was sown, in early February, in 10 different compartments, each of which had a single disease-resistant variety of wheat, oats, or barley.

Reflectance analyses were made on freshly collected, upper leaves from

each of the 10 varieties, on April 4 (plants all green), May 15 (plants starting to mature), and June 6 (plants mature). (See fig. 4.)

All 10 varieties exhibited a normal rate of development. Dates of first heading were recorded, and close-up ground photographs were taken of each plot periodically to tie in with the aerial photographs and to show the state of development on each date that aerial photos were taken.

Based on the reflectance curves, the most promising film-filter combinations were selected. Vertical aerial photographs of the entire area were taken from a fixed-wing aircraft as shown in Appendix A. Dates of photography were March 26; April 4, 7, 24; May 2, 15, 27; and June 6, 12, 20. The following film-filter combinations were used, at scales of 1/2000, 1/4000, and 1/10,000: (1) panchromatic film with a Wratten 12 (minus blue) filter; (2) panchromatic film with a Wratten 25A (light red) filter; (3) infrared film with an 89A (deep red) filter; and (4) Aerial Ektachrome (color) film with a color-correction filter, and with the proper haze-cutting filter, depending on the flight altitude.

In addition, low-altitude, large-scale aerial photos, both vertical and oblique, were taken from a helicopter, after the manner described in Appendix A. The aerial camera used was a military "K-17" with a focal length of 12 inches and a negative size of 9×9 inches. The aerial photographic equipment used in this and other tests at Davis is shown in Appendix A.

1953 Nursery Tests on Rusted Oats and Wheat

The 1953 nursery test area at Davis was planted on July 8. By that date, crops of wheat and oats grown commercially in the entire Central Valley of California had matured. Accordingly, there was no possibility that the test area would serve as an infection center from which rust might spread and damage cereal crops in the surrounding area. Varieties of wheat and oats grown in the test area were as labeled in figure 24. Each variety occupied a plot 5 feet wide and 34 feet long, in which five rows were sown. There was a spacing of 2 feet between adjacent varieties. In an effort to obtain photographic tone and color contrasts indicative of disease and of nothing else, near-isogenic varieties of plants were paired and grown side-by-side in adjacent plots. The members of any given pair differed greatly in rust susceptibility, but otherwise had nearly identical germ plasma. The Department of Agronomy at Davis was uniquely able to provide such material by virtue of its research program during the past several years, involving back-cross breeding of wheat and oats. Accordingly, the many variables, other than incidence of disease, which might have affected both crop yield and aerial photographic appearance, were virtually eliminated through use of these near-isogenic pairs.

During the period that crops were being grown in the nursery the days were bright and clear with a mean maximum temperature of 93° F. Therefore, it was necessary to provide these crops with flood irrigation at approximately five-day intervals until the plants had developed sufficiently to provide ground shade. Irrigation dates were August 3, 8, 13, 19, and 24, and September 1, 9, and 15, with some marginal flooding on September 28. On August 17, nitrogen fertilizer was applied to block VI of the nursery

(fig. 24) at the rate of 20 pounds nitrogen per acre. This was done to produce a denser and somewhat more succulent growth, thereby creating optimum susceptibility to rust of the plants grown in this portion of the nursery.

Spreader rows were used for local establishment and early, uniform spread of the rust. These rows were planted around the entire perimeter of the nursery (fig. 24). For oats spreaders, the varieties Palestine and Kanota were used, while for wheat spreaders a mixture of the varieties Bunyip, Federation, Sonora, and Pacific Bluestem was used.

Naturally-occurring California cultures of rust collected in 1952 and activated on green plants in June and July, 1953, were used. According to Stakman (personal correspondence) these were: race 2 of *Puccinia graminis avenae*, on oats; and races 11, 17, and 56 of *P. graminis tritici*, on wheat.

The initial establishment of *oats* rust was observed on August 11 (Sutton, 1953). It came from a single leaf on a spreader plant, producing three pustules. Subsequently, several spore-laden plants were brushed on spreaders. On August 19, there were several established centers in the test plots. On August 24, traces of rust were general on the oats test plots, and the original August 11 center had a localized concentration of 5 per cent. (Rust severity percentages as used here pertain to the proportion of the total leaf and stem surface area which was covered by pustules.) This increased to 25 per cent on September 8. On September 24, all test areas had attained maximum levels of rust, as shown in tables 2 and 3, Appendix B.

The initial establishment of *wheat* rust was observed on August 17. It came from a single rusted transplant which had been set in a spreader row on August 6. On August 11 and 12, a substantial number of plants in spreader rows were hypodermically inoculated with rust. These first expressed rust on August 19. In portions of the nursery where the hypodermic inoculations were not successful, spore-laden green stems were spread during late August. On August 31, there was evidence of secondary spread from the hypodermic inoculations, and traces of rust could be found everywhere. Thus, wheat rust started and climaxed about one week later than did oats rust, as shown in tables 2 and 3, Appendix B.

Reflectance analyses were made on freshly-collected upper leaves from each variety of wheat and oats on August 20 and again on September 24.

Based on the reflectance curves, vertical aerial photographs of the nursery area were taken periodically throughout the growing season, using the same film-filter-scale combinations employed in the 1953 open field tests. In addition, low-altitude, large-scale aerial photos, both vertical and oblique, were taken from a helicopter as described in Appendix A.

Dates of aerial photography for the nursery area were September 1, 12, and 24, and October 3 and 15. Close-up ground photographs were taken periodically to tie in with the aerial photographs and to show the state of development on each date that aerial photos were taken (figs. 11 and 22).

Even the most susceptible varieties of wheat and oats did not attain 100 per cent rust severity. In the case of early-maturing varieties, this was because of the relatively low infection on the flag leaf; in the case of the late varieties, it was due to their premature ripening as the result of a hot wind on October 2, which also caused a great deal of stem breakage on some

varieties (table 1). However, basal plant parts of *all* susceptible varieties had 100 per cent stem rust at climax, while severity for the entire leaf and stem area of these varieties ranged, for the most part, between 70 and 90 per cent. The resistant isogenic mates to these varieties mostly exhibited rust severities of 0 to 25 per cent at climax. Accordingly, failure of the susceptible varieties to display maximum rust severity did not appreciably detract from the tone and color contrasts sought between healthy and diseased cereal crops, as will be shown in succeeding photographs.

No leaf rust was observed in the nursery until October 5, by which time the crops were ready for harvest. Thus, leaf rust was not a complicating factor in any of these tests on black stem rust.

The 1954 Tests

At the conclusion of the 1953 nursery tests it was recognized that there was need for some additional testing to determine what operational significance this aerial photographic technique might have. Specifically, there remained the need to investigate the extent to which some particular disease, infesting a certain kind of cereal crop in a large, open field, could be assessed by means of aerial photography. To add further to the realism of such a test, the crop being investigated should be one that had become disease-infested by natural means, and that was surrounded, at the time of study, by other cereal crops, either healthy or infested with some different disease.

An 80-acre block on the Davis campus was selected for one such test. As shown by figure 7, this block contained the four most common dry-land cereal crops (wheat, oats, barley, and rye) growing in discrete blocks, each 10 acres or larger in size.

All blocks had been sown early in February. By about April 1 a single spore shower of *Puccinia graminis avenae* apparently landed at the south end of the 10-acre plot of Palestine oats. Subsequently the disease spread from this infection center (and possibly from other spore showers of lesser size) until, by May 15, the entire 10-acre field was spotted with infection. The adjacent fields of wheat, barley, and rye remained relatively disease-free. The same array of vertical and oblique aerial photographs as had been used in the previous tests at Davis were taken, using both helicopters and fixed-wing aircraft as the aerial camera platforms. Dates of aerial photography were April 2 and 21; May 2, 12, and 21; and June 6. As in previous tests, ground observations and ground photographs were made at critical stages in the development of the crop and its pathogen.

One complicating circumstance in this test resulted from a driving rain which occurred on May 1, and which "lodged" (*i.e.*, blew to the ground) much of the grain in the 80-acre test plot. The area of Palestine oats, on which attention had by then been concentrated, was hit very heavily. However, as shown in figure 16, this area still yielded valuable information.

An open field test involving black stem rust on wheat was also conducted in the spring of 1954.

Concurrent with the above open field test, another nursery plot test was conducted. This dealt, on a relatively small scale, with the problem of differentiating black stem rust on oats and wheat from various other

cereal crop diseases of importance in the Davis area, including yellow dwarf virus (scientific name not yet assigned) on oats and barley, and net blotch on barley. Aerial and ground photographs of the nursery area were obtained on the same dates as for the concurrent open field test.

Finally, a test was made to determine the feasibility of detecting rust infection centers in their overwintering grounds along roadsides and ditch-banks.

RESULTS

The illustrations of cereal crops published herein are related to the tests just described as follows: Figure 2 is from the 1952 nursery test; figures 3 through 9 are from the 1953 open field tests; figures 10 through 15, 22 through 30, and figure 32 are from the 1953 nursery tests; the remainder are from the 1954 tests. The results shown in these figures can be understood only through an appreciation of certain characteristics of the four films used.

As the term *panchromatic* implies, this film is about equally sensitive to all colors. The infrared film used is sensitive not only to infrared but also to much of the visible portion of the spectrum. Accordingly, in order to take true infrared photographs it is necessary to use a deep red filter, such as the Wratten 89A, to screen out the visible portion of the spectrum. Spectral sensitivity curves for both the panchromatic and infrared films are shown in figure 10B.

Kodak Ektachrome Aero film (high contrast) has three emulsions coated on a single film base. The emulsion next to the film base is sensitive to red light, the middle emulsion to green light, and the top emulsion to blue light. Each emulsion has incorporated in it a chemical compound known as a coupler, which reacts with certain film developing agents in the oxidized state to form a dye of a particular color. When the exposed film is processed, the couplers in the three emulsions yield dyes which are cyan, magenta, and yellow, respectively, thereby producing a positive image on the film which is viewed directly as a color transparency. Although the spectrophotometric characteristics of the object and of its photographic image are not identical, the resulting transparency is usually a remarkably accurate representation, in full color, of the object itself (Tarkington, 1953).

Camouflage-detection film is a color film in which the three emulsions, coated on a single film base, are sensitive to visible green, visible red, and infrared, respectively. Visible blue is absorbed by a Wratten 15 filter which is used in conjunction with the film. The sensitivity of the film is such that highly infrared-reflective objects, such as healthy green vegetation, register as visible red; green objects which are not highly infrared-reflective register as blue; and red objects which are not highly infrared-reflective register as green. Since blue light is eliminated, blue objects register as black. Actually, a sharp separation between the visible red and infrared portion of the spectrum is seldom attainable. Accordingly, red objects which are not highly infrared-reflective, such as the rusted leaves of certain cereal crops, record as yellow or brown.

In reproducing the photographs for publication, great pains have been taken to duplicate the originals. In no instance have the photos been retouched to illustrate features not discernible on the originals.

Among the unique aspects of this type of research is the fact that the results can be expressed primarily by means of photographs which speak for themselves. While the ensuing photographs are accompanied by captions and some supporting text, the reader is urged to do his own photographic interpretation to the maximum extent possible. He also is urged to study the stereograms three-dimensionally, either by means of naked-eye stereo vision, or with the aid of a stereoscope. This is of particular importance because much of the detail present in the original photos, and seemingly lost in the process of reproduction, is regained when the stereograms are viewed three-dimensionally. Even so, it will be noted that, in a few instances, pertinent photographic detail discernible in the original photographs, and therefore mentioned in the captions, is not discernible in the present reproduction.

Photo Interpretation of Healthy Cereal Crops

In order to understand the results obtained in tests with healthy cereal crops it is first necessary to understand certain interrelationships of the leaf structure and light reflectivity of such plants.

Figure 5 is a schematic drawing of the cross-section of a healthy, green cereal leaf. The marked similarities among the April 4 reflectance curves shown in figure 4 are explained from the following analysis of this drawing:

Light from the "blue" part of the spectrum, having wave-lengths of approximately 400 to 500 millimicrons, is largely absorbed by the leaf's green pigment, chlorophyll, and used as the source of energy in photosynthesis. Accordingly, only about 10 per cent of the incident sunlight in this part of the spectrum is reflected to the camera by the green plant, as shown in figure 4.

Light from the "green" part of the spectrum, having wave-lengths of approximately 500 to 600 millimicrons, is reflected to a much higher degree by the chlorophyll, thus accounting for the green appearance of the leaf in color photography, and for the 20 per cent reflectance peak in this part of the reflectance spectrum shown in figure 4.

Light from the "red" part of the spectrum, having wave-lengths of approximately 600 to 700 millimicrons, is largely absorbed by the chlorophyll and used in the photosynthetic process, much as the blue light is. Accordingly, only about 10 per cent of this light is reflected to the camera by the green plant.

In that portion of the infrared spectrum with which we are concerned, ranging from approximately 700 to 900 millimicrons, 80 per cent or more of the incident sunlight is reflected from the green leaf, as shown in figure 4. This fact accounts for the popular misconception, as reported by Ryker (1933) and others, that chlorophyll reflects infrared light to a very high degree. Actually, since chlorophyll is almost completely transparent to infrared light, the explanation offered by Clark (1946) seems much more plausible, namely, that this high infrared reflectance results from the spongy structure of the mesophyll tissue of the healthy green leaf. Many objects

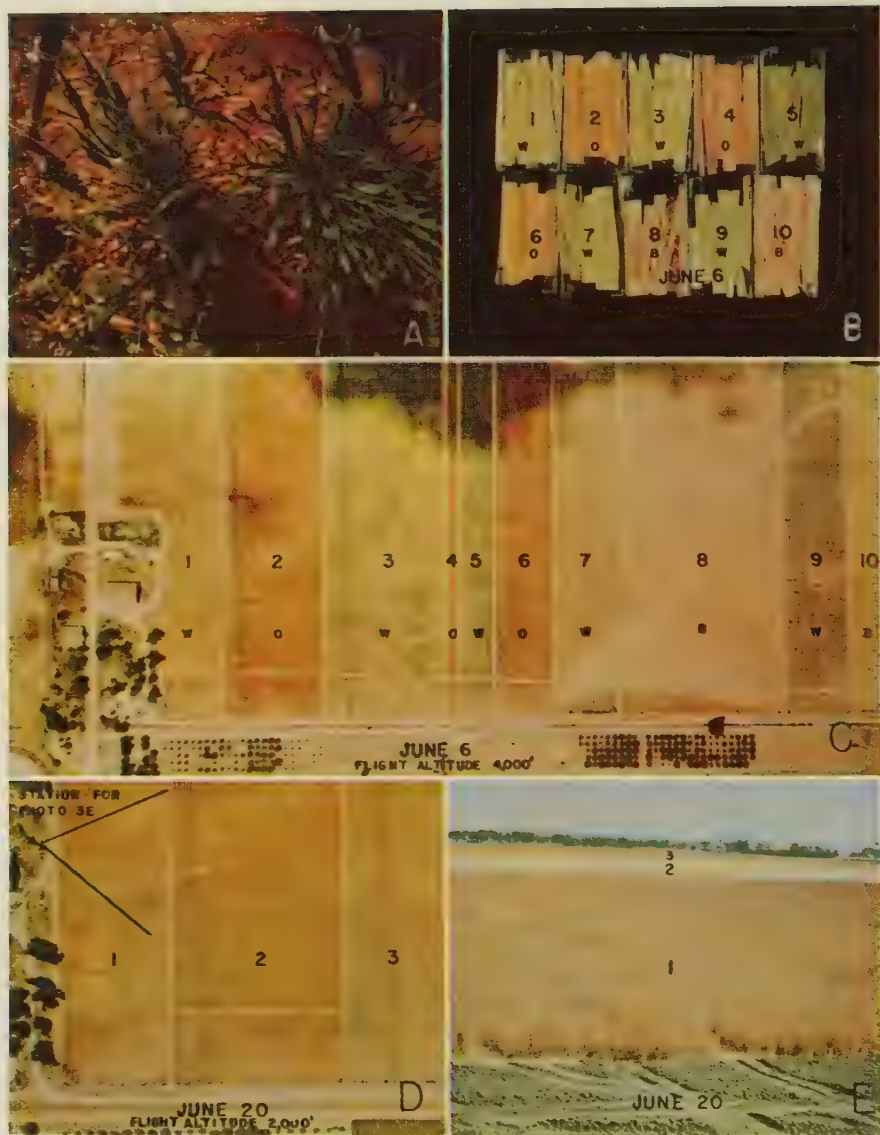


Fig. 3. Ektachrome photos of healthy cereal crops grown in an 80-acre block at Davis, California. A: Close-up of oats showing that primarily upper leaves (rather than stems or inflorescences) reflect radiant energy to the camera in a *vertical* photo. B: Upper leaves of 10 varieties of wheat (W), oats (O), and barley (B), mounted between glass slides for measurement of spectral reflectance in a spectrophotometer. C: Vertical aerial photo of 10 plots from which leaf samples shown in B were collected on same date. Note close similarity between aerial photo colors for entire plots, C, and colors of corresponding leaf samples, B. Figures A, B, and C indicate validity of using spectral reflectance of upper leaves to predict tones or colors of cereal crops on *vertical* aerial photos. Note reduction of color contrast in cloud shadow at top of C, indicating importance of taking photographs in bright sunlight. D: Vertical view, portion of same area two weeks later when leaf color differences had diminished. E: Oblique view of area bracketed in D, taken on same date. Note increased color contrast between oats at "2" and wheat at "1" and "3," in E, as compared with D, showing that color of inflorescences ("heads") is far more important in oblique than in vertical views.

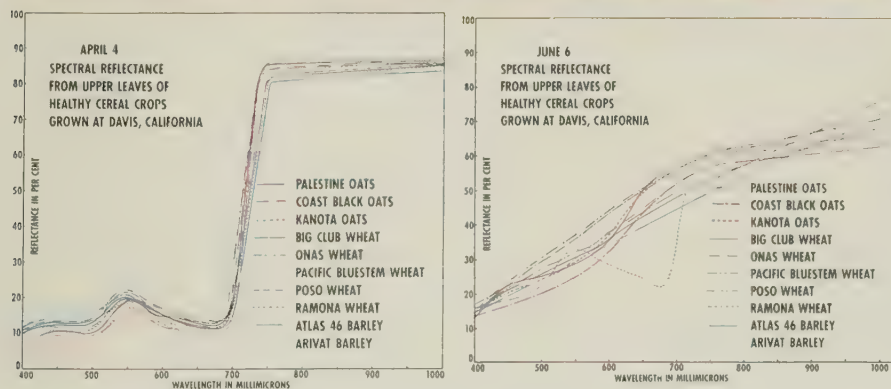
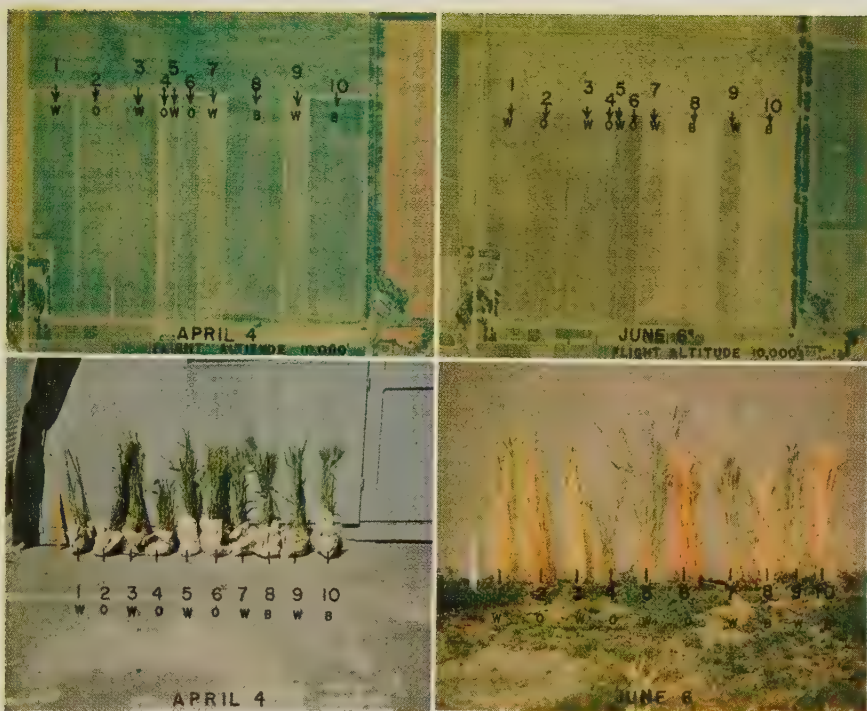


Fig. 4. Ektachrome photos and spectrophotometric curves for the healthy cereal crops shown in figure 3. From top to bottom are shown: vertical aerial photos (flight altitude, 10,000 feet), crop samples, and foliage spectral reflectance curves, respectively, on April 4 (left column) and June 6. Note marked similarity of all spectral reflectance curves on April 4, when chlorophyll content and leaf structure of all varieties were quite uniform. Consistent with this, no aerial film-filter combination used on April 4 provided tone or color differences that would permit crop identification. (Plots 4, 7, and 9 appear light in the top left photo merely because of the relative sparseness of their stands at that early date.) However, by June 6, as shown by the right-hand series, the upper leaves of most varieties of oats were beginning to turn brown and those of barley to turn golden, while those of wheat remained green for several more days. Oblique views, in which the heads are conspicuous, are also helpful in differentiating among healthy cereal crops at this time, as indicated by figure 3E.

having a similar spongy structure, such as foam, soap bubbles, snow, or the pith of a plant stem, usually appear a brilliant white because they are such good reflectors of light. In a green plant, however, as previously explained, only infrared light is free to bounce back and forth within the leaf tissues, unaffected by the chlorophyll pigment. Hence, only infrared light is reflected to this high degree from a green plant.

In the frequent instances where cereal crops approach maturity at various rates, seasonal differences in the light reflectance of leaves of the various species may become discernible. In figure 3B, for example, it is apparent that by June 6 all three varieties of oats had leaves which were somewhat browner than those of wheat and barley. This is also indicated for the same date, in figure 3C, by the brownish color of plots 2, 4, and 6 (the three oats plots), and in figure 4 by the right-hand column of photos, which also apply to the June 6 condition.

The unique golden color of barley on this same date is best illustrated by the top right photo of figure 4, in which the two varieties of barley appear in blocks 8 and 10. In general, the varieties of wheat shown in this plot tended to remain green longer than did the other cereal crops, but it will be noted that on June 6 the wheat in blocks 1 and 3 had much the same color in the vertical view as did the oats in block 2. By June 20, blocks 1, 2, and 3 were virtually indistinguishable in the vertical view, as shown by figure 3D. However, in the oblique photo taken of the same three blocks on the same date (fig. 3E), the yellowish panicles of the oats in block 2 contrasted sharply with the brownish heads of wheat in blocks 1 and 3.

The foregoing results indicate the importance of aerial photo specifications in a project such as this. Although it may not always be possible to identify each type of cereal crop in its healthy state from a single set of aerial photos, this problem may be solved by using two or three sets of photo-cover flown to proper specifications with regard to dates, angles, film-filter combinations, and other pertinent factors.

Additional examples are given to document this important point: At about the time of first heading (in April at Davis), all varieties have essentially the same foliage reflectance, as shown by the left column of figure 4. Consistent with this fact, it was noted that such small differences in color as appeared in vertical photos taken at that time were not a function of variety of cereal crop, but of density of the stand. However, in the oblique view, wherein heads are more conspicuous and leaves and ground are less conspicuous, barley and rye were found to have unique color values at that time of year (fig. 7, top photo). In figure 6, it will be noted that the stands of grain in the oblique views (left column) appear to have a uniformly high density, whereas in the corresponding vertical views (right column) many portions of the area are seen to be of quite low density. Also in figure 6, the two middle photographs indicate a mottling of healthy stands, as they approach maturity, which might superficially be confused with the mottled pattern caused by certain cereal crop diseases.

It is already apparent that the problem of identifying cereal crops and their diseases from aerial photos is a complex one. Observations which are valid in one cereal-producing region may not be valid in another where dif-

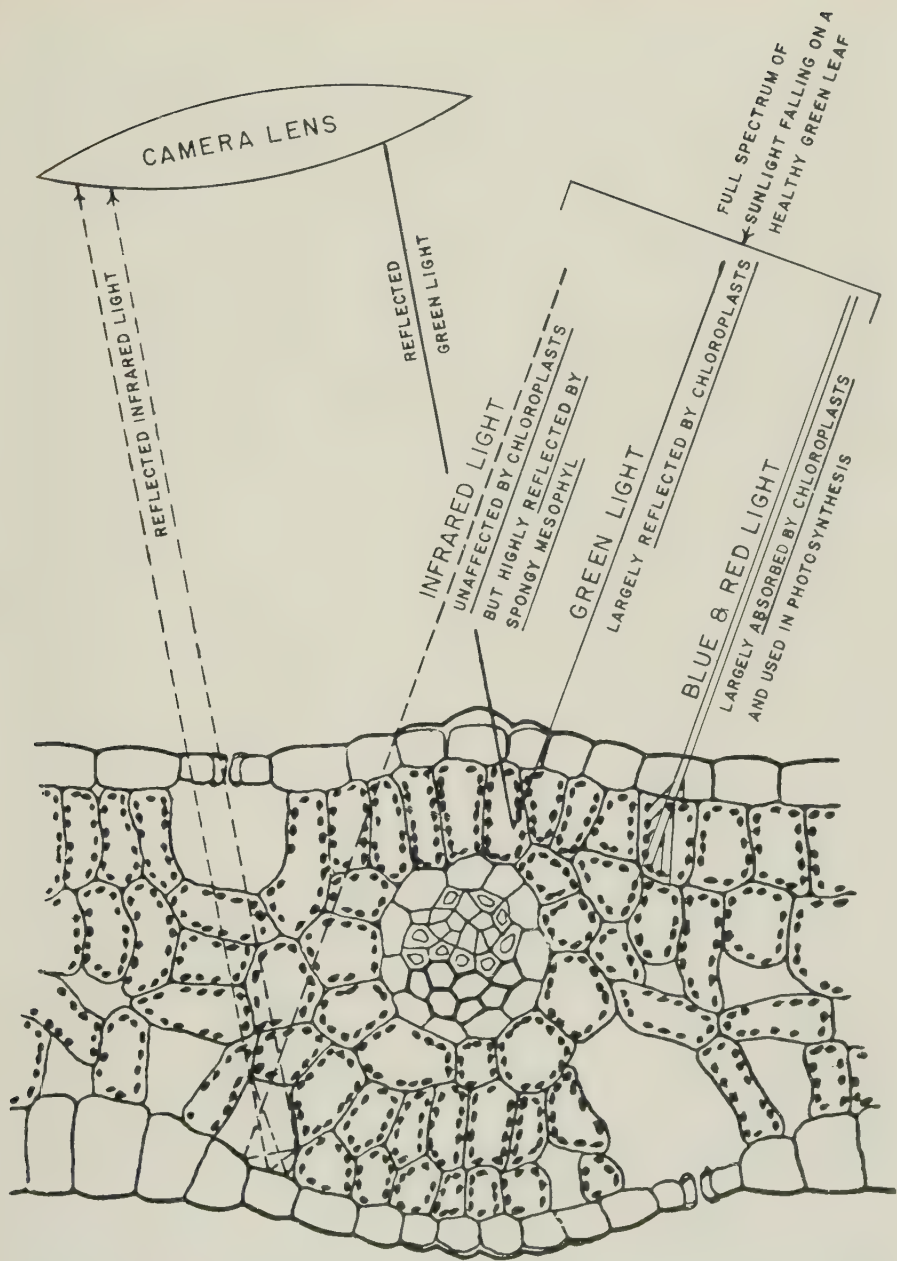


Fig. 5. Schematic drawing of cross-section of a healthy oats leaf (after Eames and MacDaniels, 1947). Note that certain wave lengths are largely absorbed while others are reflected to a high degree, either by the chloroplasts or by the spongy mesophyll tissue. Reflection from the cuticle on the upper surface of a green leaf is relatively minor (Clark, 1946) and therefore is not diagrammed. The spectrophotometric curves for green leaves shown in the lower left diagram of figure 4 might have been predicted with considerable accuracy from the information contained in this illustration. Should this leaf become diseased, its spongy mesophyll (which now is turgid and highly reflective of infrared light) would either collapse or be plugged by hyphae of the fungus. This would happen long before the leaf's green color started to fade. Hence the disease would be detectable much sooner on infrared than on panchromatic photography, as shown in figures 12 and 14.



Fig. 6. Ektachrome oblique and vertical photos of a mixture of healthy cereal crops at three seasonal states of development. Top: About the time of first heading for most varieties. Center: Crops nearing maturity and exhibiting a mottled effect which the photo interpreter must not confuse with disease. Bottom: Harvest time. Brackets drawn on the vertical photos indicate camera stations and fields of view for the corresponding oblique photos.

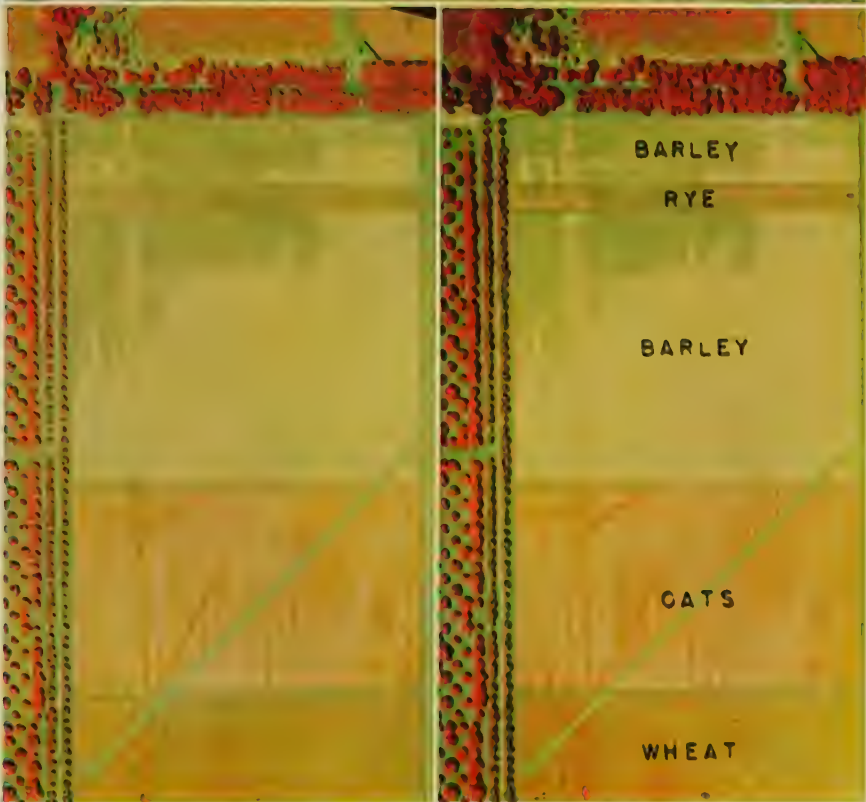


Fig. 7. Top: Aerial ektachrome oblique view of healthy wheat, oats, barley, and rye taken at about the time of first heading. Note unique blue-green color of rye. Bottom: Vertical stereogram of same area taken just before crops have matured, using camouflage-detection film (flight altitude, 4,000 feet). Compare with figures 8 and 9.



Fig. 8. Panchromatic-minus blue vertical stereogram of same area as figure 7, taken on same date.

ferent varieties are grown, different soil and climatic conditions prevail, and different diseases are present. However, the remainder of this paper will endeavor to demonstrate that: (1) in one representative area (the Davis area) the major cereal crops and their diseases usually can be identified from aerial photos taken to the proper specifications; and (2) both the photo specifications and photo recognition features necessary for making the identifications can be set forth in a systematic fashion that even the layman can comprehend.

Before proceeding to the photo interpretation of diseased cereal crops, however, it is important to summarize the information gained from the foregoing photographs and reflectance analyses of healthy cereal crops:

(1) In the vertical view, light reflectivity from the plant's leaves, rather than from its stem or inflorescences, governs the photographic tone or color of the plant.

(2) In the oblique view, light reflectivity from the plant's inflorescences (once they have been formed) governs the photographic tone or color of the plant in very large measure.

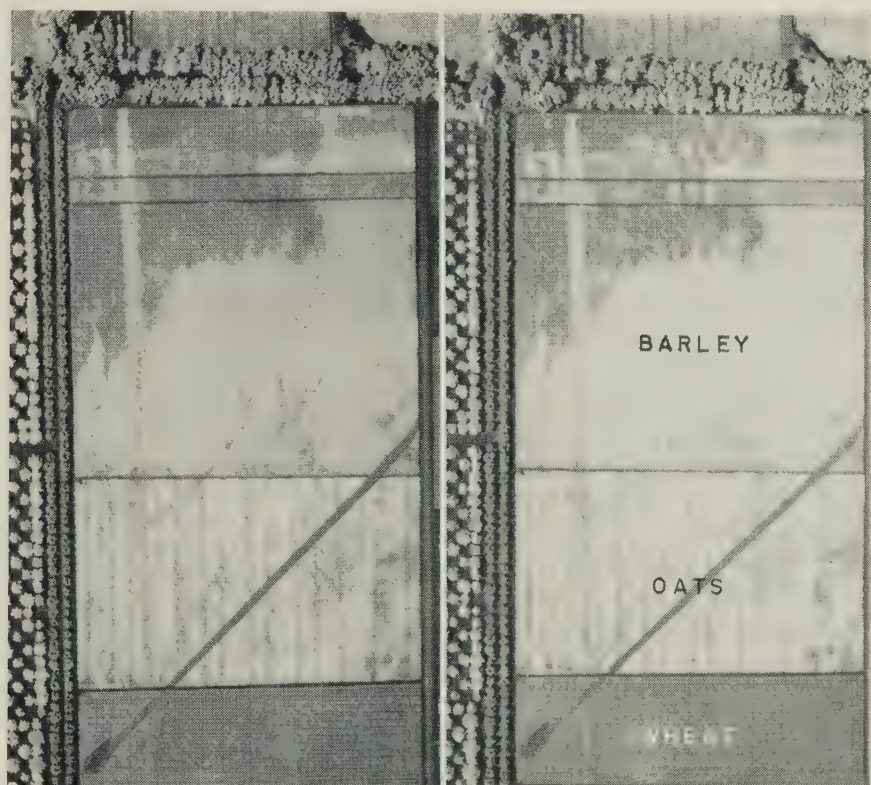


Fig. 9. Infrared-89A vertical stereogram of same area as figures 7 and 8, taken on same date. Note that aerial ektachrome photography (figs. 3 and 4) is superior to panchromatic, infrared, or camouflage-detection (figs. 7, 8, and 9) for identifying healthy crops at this stage of maturity.

(3) Up to the time of first heading, all varieties of wheat, oats, and barley included in this study exhibited essentially the same light reflectivity throughout the range here studied (400 to 900 millimicrons). Consistent with this, there is no film-filter combination which will give a tone or color difference permitting the separation of these three species at this early stage in their development.

(4) As healthy cereal crops approach maturity, barley is usually identifiable on vertical aerial photos by its golden color, oats by its brown color, and wheat by the persistence of its green coloration for many days after the other crops have matured.

(5) Rye is frequently identifiable, particularly on oblique aerial photos, from shortly after it germinates until the time of maturity, because of its unique bluish-green coloration (fig. 7).

(6) The mottled appearance of healthy grain fields as they approach maturity (fig. 6) necessitates care in interpretation on aerial photos, lest such fields be considered diseased.

Photo Interpretation of Rust-infested Oats

As in the case of healthy plants, the interrelationships of leaf structure and light reflectivity of plants must be understood in order to understand the results obtained in these tests. As shown in figure 10A, there is a marked reduction in infrared reflectivity of oats leaves very shortly after the plant becomes diseased. (The slight increase in reflectivity of orange and red light shown in figure 10A does not develop until some two or three weeks later.) The explanation for this early loss in infrared reflectivity is found by again referring to the structure of the leaf, as shown in figure 5. Even while the plant is still a normal green color and exhibits a healthy appearance to the naked eye, the hyphae of the invading fungus fill the intercellular spaces of the spongy mesophyll tissues (Hart, 1931; Stakman, 1956). Since the mesophyll then no longer exhibits the properties of a spongy structure, it loses its high reflectivity of infrared light, as shown in figure 10A. From this curve, together with the film sensitivity curves of figure 10B and the filter transmission curves of figure 10D, it was predicted that, on photos

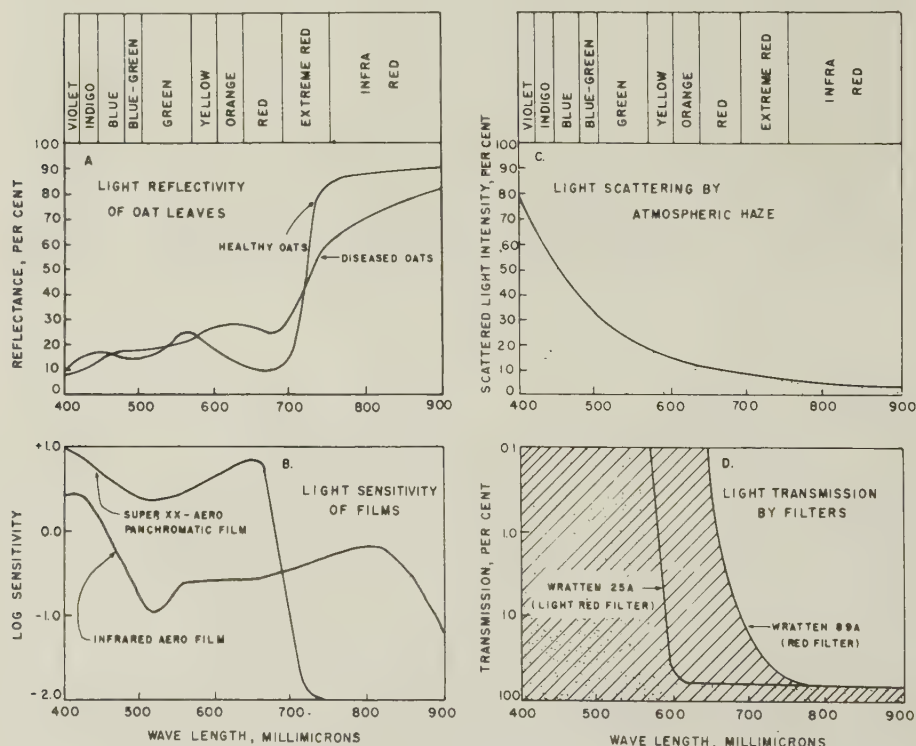


Fig. 10. See text for a discussion of the significance of these spectrophotometric curves in predicting the aerial photographic tones of healthy and diseased oats. In the top left diagram above, the loss of infrared reflectance caused by disease precedes the gain in visible red reflectance by many days. This explains why the disease is first detectable by its dark tone on infrared-89A photographs (fig. 12, top right) and only later by its light tone on panchromatic 25-A photographs (fig. 12, lower left).

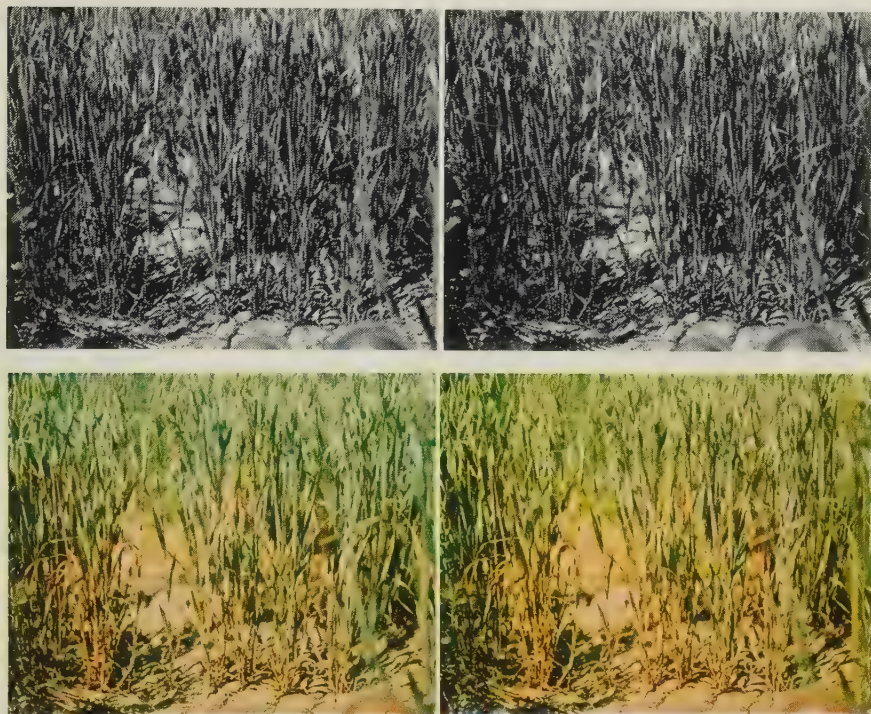


Fig. 11. Stereoscopic ground photos showing black stem rust on oats on September 11 when rust severity was approximately 25 per cent. Top: Panchromatic Super XX film with no filter. Bottom: Daylight Ektachrome film with no filter. Note that the disease cannot be detected on the black-and-white photos even at this 10-foot distance because the wrong film-filter combination was used, as shown by figure 10. However, the disease is readily seen, even at 10,000 feet, when the proper film-filter combination is used, as shown by figure 13. This same area, photographed from the air 10 days earlier, is shown in figure 12 (top right) and in figure 13.

taken with infrared film and through a deep red (89A) filter, diseased oat plants would appear dark in tone while healthy oat plants would appear light in tone, even though the diseased blocks had a rust severity of less than 5 per cent at that time. Likewise it was predicted that no such tone difference would be detectable at this early date on conventional "panchromatic-minus blue" photographs. Comparison of the top left and top right photos of figure 12 shows the accuracy of this prediction. Finally, it was accurately predicted that no color contrast would be detectable at this early date on aerial Ektachrome photography. (See oats blocks in top photo of fig. 24.)

Tone contrasts such as are shown in the low-altitude photos of figure 12 (top right) are often difficult to maintain on high-altitude aerial photography because the scattering of light by atmospheric haze tends to reduce the tone contrast very markedly (Duntley, 1948a). However, this scattering of light by atmospheric haze is very slight in the infrared range as shown

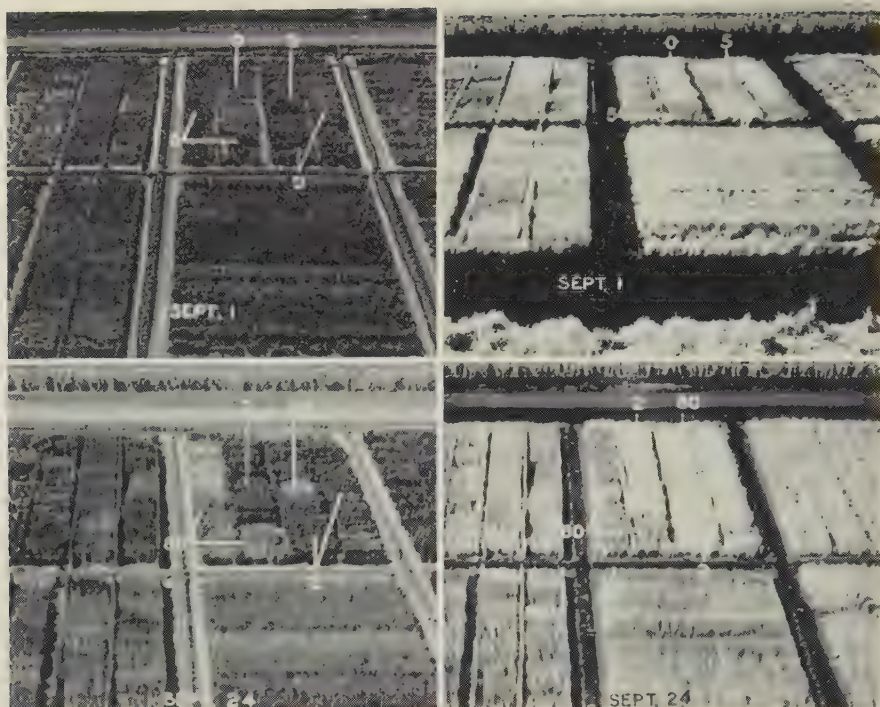


Fig. 12. Aerial oblique photos showing black stem rust on oats at two different stages of development. The two photos on the left were taken with panchromatic film and a 25-A filter; the two photos on the right, with infrared film and an 89-A filter. Note that the diseased areas were readily detectable by their dark tone on infrared photographs as early as September 1 (top right) even though the severity of disease then was only 5 per cent. By September 24, the diseased areas had a severity of 80 per cent and were detectable by their light tone on panchromatic photographs (lower left). These tone contrasts were predicted from the spectral diagrams of figure 10.

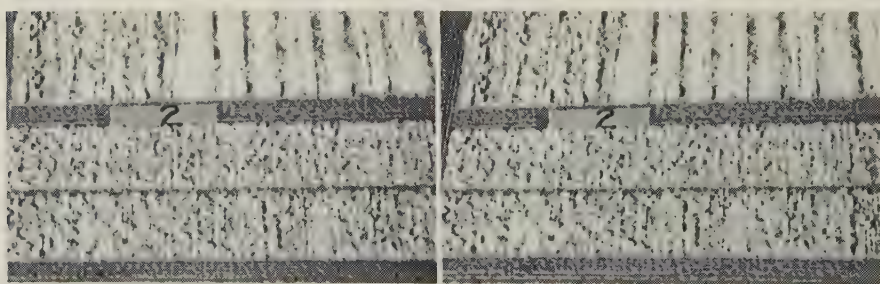
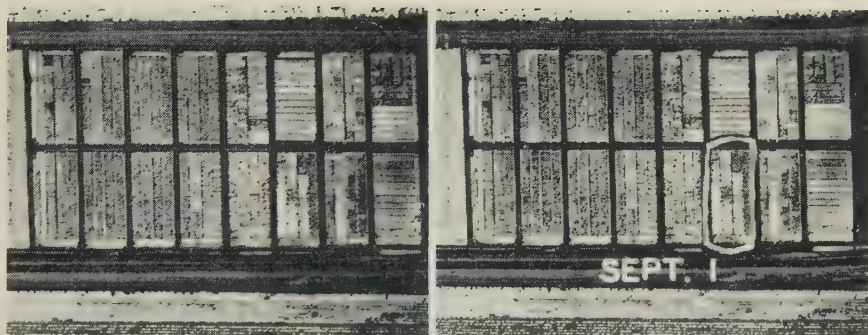
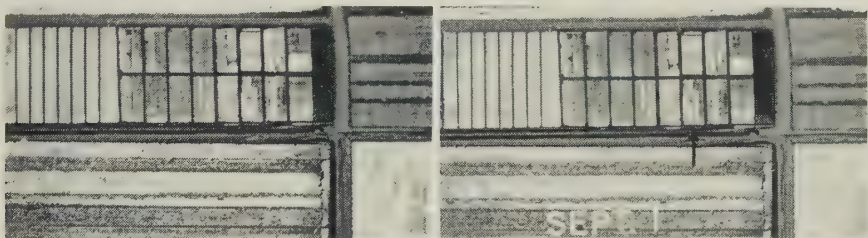


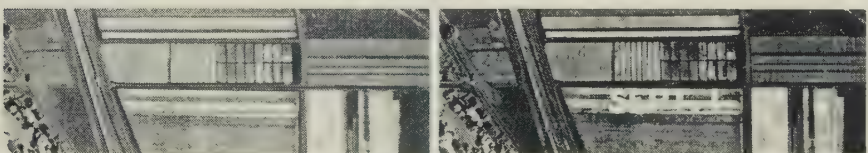
Fig. 13. Aerial oblique stereogram of *healthy* oats photographed at same state of development as those shown in top right photo of figure 12, and with same film-filter combination (infrared-89A). The successive rows contain varieties which differ markedly in their susceptibility to oats rust, including the varieties shown in figure 12. Notice that, in this healthy state, all varieties exhibit essentially the same light photographic tone. Accordingly, the dark tones shown by these varieties in the diseased state on infrared photos (fig. 12) are attributable solely to the disease itself. The spectral diagrams of figure 10 confirm this.



Flight altitude 2,000 feet.



Flight altitude 4,000 feet.



Flight altitude 10,000 feet.

Fig. 14. Vertical photo stereograms of healthy and rust-infested oats taken with infra-red-89A at three different scales. The small, diseased square labeled "5" in top right photo of figure 12 is clearly seen in the area circumscribed in the top right photo above. Note that this same square also is discernible, above, at progressively smaller scales. Because there is very little scattering of infrared light by atmospheric haze (see top right diagram, fig. 10) there is very little reduction in tone contrast between diseased and healthy plants when photographed from progressively higher altitudes, as shown above. However, care must be taken to avoid confusing diseased areas on these infrared photos with bare ground or flooded areas which also photograph dark in tone.

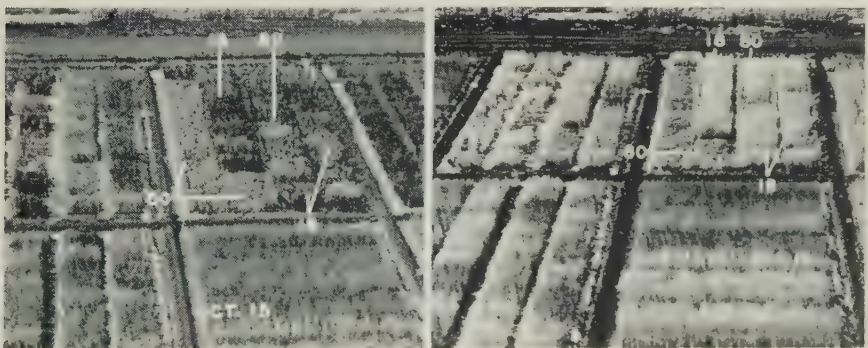


Fig. 15. Aerial oblique photos of the same area, taken after the healthy oats had matured and the diseased oats had collapsed. Compare with earlier photos of the same area (fig. 12). Yield reduction in the diseased oats shown here exceeded 70 per cent (table 1, Appendix B).

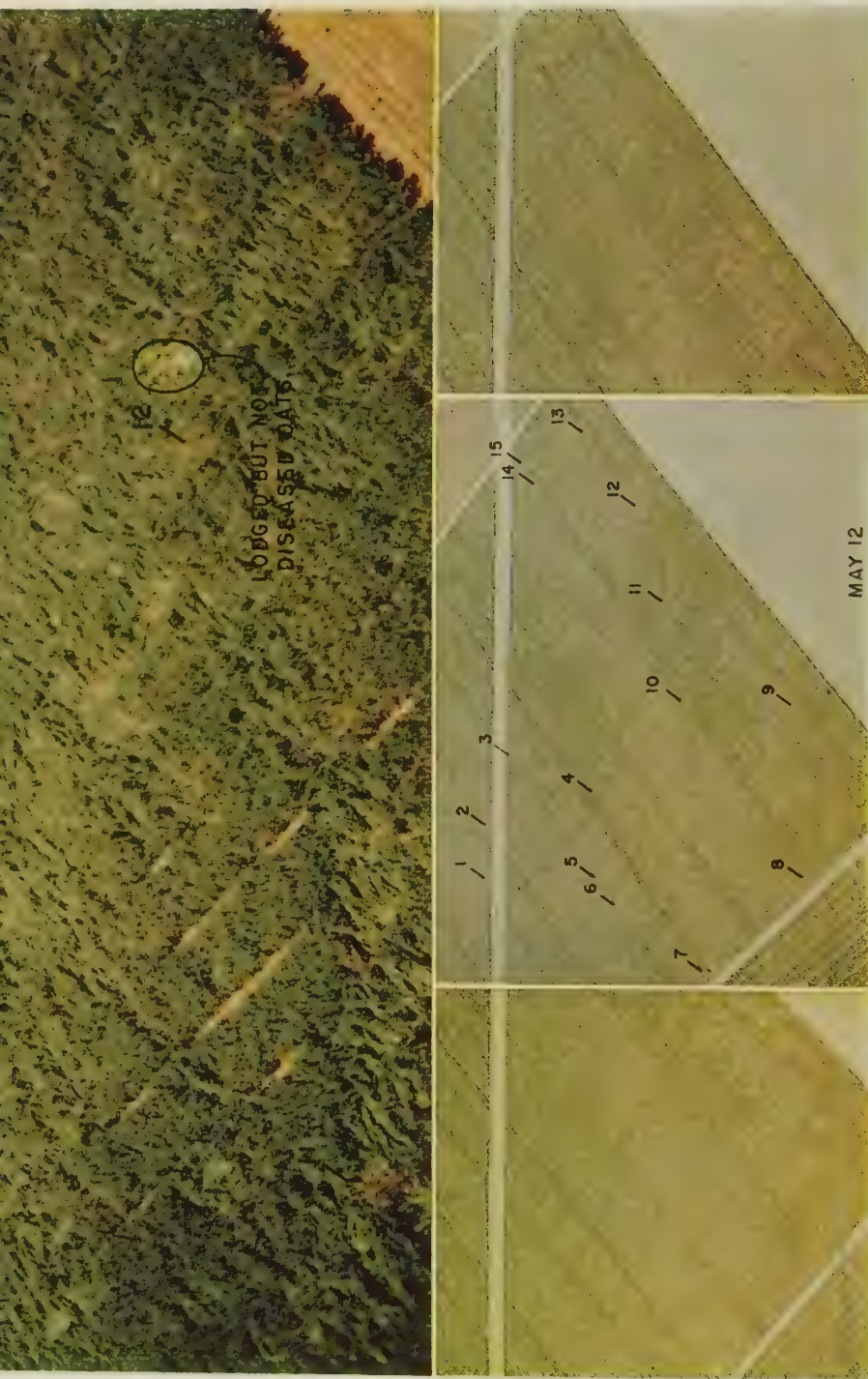


Fig. 16. Aerial ektachrome photographs of naturally-occurring oats rust infections. Top: Large-scale aerial oblique photo on which individual diseased plants are readily detected at areas "11" and "12," and can be differentiated from lodged, but healthy oats. Bottom: Stereo triplet of the same field from a flight altitude of 2,000 feet. Area "8" was the first infection center to become established in this field. Each of the 15 largest rust centers in the field was first identified from these aerial photos and later confirmed by ground observation. Note that much of the grain has been lodged by a driving rain.



Fig. 17. Ektachrome photos of oats rust infection centers. A single infected oats plant was emplaced at one end of the healthy field of oats, as shown in photo A, above. This plant was barely discernible on the same date in the aerial oblique view, B. By May 12 the disease had spread from this infection center as shown in C, and by May 12 as shown in D. Aerial photos E and F are an oblique stereogram of this area as seen on May 12. G and H, taken with camouflage-detection film and Ektachrome film, respectively, show a similar infection center which established itself naturally in an open field, probably as the result of a "spore shower." By detecting and treating the infection centers at this stage of development, rust damage might have been materially reduced. This same area is labeled "3" on the aerial photos of figure 16, taken on the same date. It was readily detected on the original color photos from which figure 16 was made.



Fig. 18. Panchromatic-25A (left photo) and infrared-89A aerial views of the same rust infection center as shown in figure 17 E and F, and on same date.

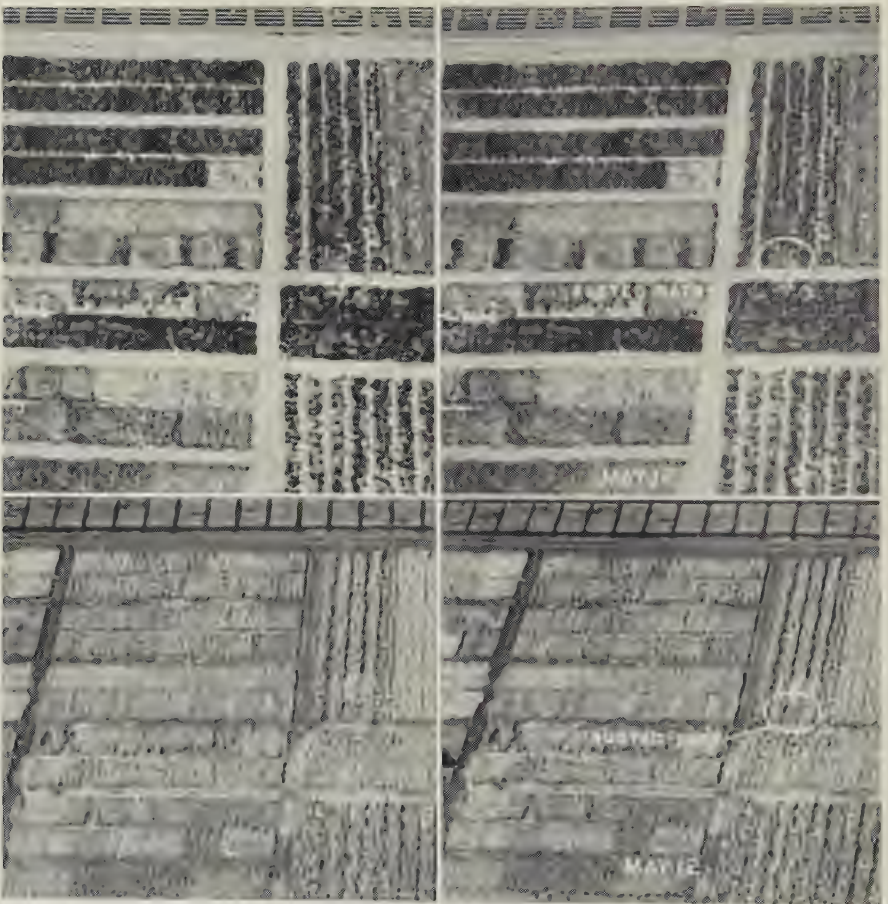


Fig. 19. Panchromatic-25A (top stereogram) and infrared-89A aerial views of same rust infection center as shown in figures 17 and 18, taken on same date but from a greater distance.

in figure 10C. Accordingly, it was predicted that there would be very little reduction in tone contrast between the diseased and healthy oats on infrared-89A photographs taken at very high altitudes. Again predictions based on spectral analyses were borne out by actual results, as shown by figure 14, in which the tone contrast between diseased and healthy oats is essentially as great on photographs taken at 10,000 feet as on those taken at much lower altitudes. This result is of especial significance since aerial photographs probably would have to be taken from altitudes of 10,000 feet or more in order to provide complete and economical coverage of the vast areas in which a search for rust infection centers would have to be made. In this connection it should be emphasized that the reduction of infrared reflectance associated with the disease occurred, in this case, from two to three weeks earlier than the increase in orange and red reflectance (fig. 10A). The lack of sensitivity of the human eye to infrared light probably explains our previous lack of appreciation of this important fact. To the extent that high-altitude, small-scale, aerial photography might have to be relied upon as the means for attempting the earliest possible detection of diseases in our vast cereal-producing areas, it is especially fortunate that the earliest symptoms of the disease are in this infrared portion of the spectrum where high-altitude haze interference is at a minimum.

As shown by the bottom left photo of figure 12 and by the bottom photo of figure 24, the diseased areas eventually become readily discernible by their *light* tone on panchromatic-25A photographs and by their yellow color on aerial ektachrome photographs. These results also were predicted from the spectral data of figure 10. In relation to possible control of the disease, however, these results are of limited significance because by the time the disease is discernible on these two types of photography, the rust is well on the way to attaining epiphytotic proportions. However, either panchromatic or color photography may be superior to infrared photography (bottom right photo of figure 12) for illustrating the eventual spread of the disease, since even the healthy plants lose much of their infrared reflectivity as they approach maturity. This is attributed to a partial collapse of the spongy mesophyll tissues in the leaves of healthy plants, brought about by a general drying out of the plant as it approaches maturity, with a consequent loss in the turgor pressure of cells in the spongy mesophyll. Without such turgor pressure, the cells are no longer able to remain in the distended state that gives a spongy structure to the mesophyll tissue and a consequent high infrared reflectivity to the plant.

Other factors relative to the photo interpretation of rust-infested oats, including the value of color photography and the opportunities for picking out rust-infection centers in open fields, are indicated by the captions to figures 11 through 21.



Fig. 20. Aerial ektachrome (left) and camouflage-detection film views of a naturally-occurring oats rust infection center. This area is typical of the overwintering grounds for rust in the Davis area, where overflow from irrigation pipes or ditches may help keep wild oats plants green the year 'round.



Fig. 21. Panchromatic-25A (left) and infrared-89A views of the same rust infection center. This center is much more conspicuous on the infrared photo than it was to a ground observer. In areas where such centers are not too numerous, early detection of them by infrared photography, followed by prompt treatment (e.g., application of sulfur with a hand-duster) might retard the rate of spread of the disease to near-by grain fields, thereby greatly reducing losses (Stakman, 1956).

Photo Interpretation of Rust-infested Wheat

Most of the results on photo interpretation of wheat rust are apparent from a study of figures 22 to 32. Accordingly, only a few important points will be elaborated here.

1. Analysis of the spectral curves of figure 23 permitted accurate predictions to be made of the photographic tone and color values which healthy and diseased crops would exhibit on various film-filter-scale combinations.

2. Rusted wheat plants at Davis characteristically had a more reddish color than did rusted oats plants. This is indicated by the top stereogram of figure 28 and by the foliage reflectivity curves of figure 23A. This reddish coloration was accentuated somewhat, particularly in the vertical photographs, by a heavy deposition of the urediospores of *Puccinia graminis tritici* in the immediate vicinity of the most heavily rusted rows of plants. (See top stereogram, figure 22.) According to Christensen (1942) and Stakman (1947), more than 50,000 billion of these spores, per acre, are found in an area of heavily rusted wheat. Using the average dimensions which they give for such spores, this would represent a uniform layer, 5 to 10 spores



Fig. 22. Stereograms of rusted wheat. Top: Plants on September 24, still green but heavily infested with black stem rust. Note red coloration of soil due to surface layer of spores. (This is the plot labeled "75" on all succeeding September 24 aerial photos.) Bottom: Same plot, 10 days later. Yield reduction due to rust in this plot was in excess of 70 per cent (table 1, Appendix B).

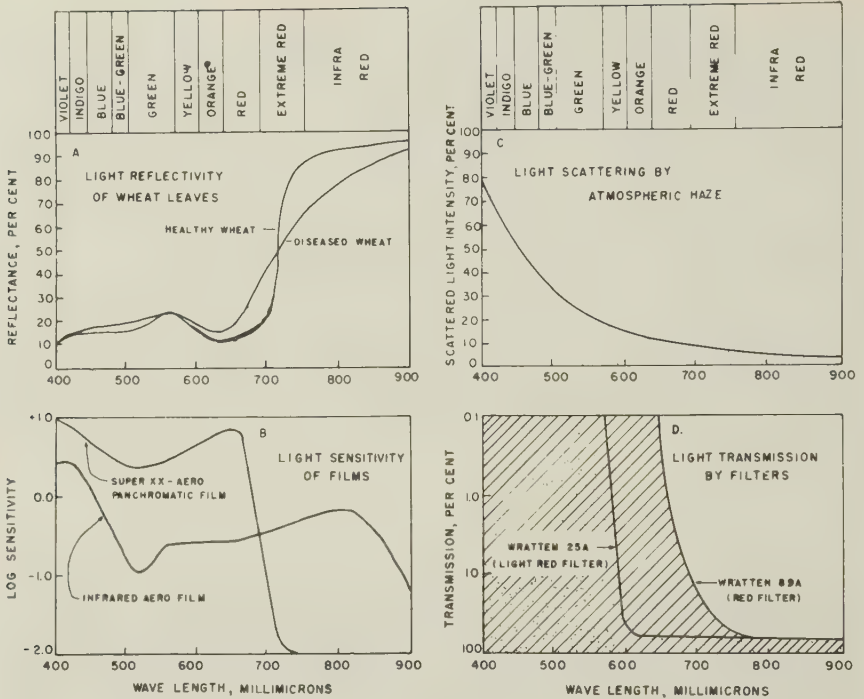


Fig. 23. A comparison of the spectral reflectance of healthy and diseased wheat, as shown above, with that of healthy and diseased oats, as shown in figure 10, indicates the useful predictions possible through spectral analyses. Specifically, if vertical aerial photos were taken two to three weeks after first heading, of an area containing both wheat and oats, and in which rust showed strong local development, then: (1) on aerial ektachrome photos rusted wheat would be expected to photograph red, rusted oats yellow or yellowish red, and healthy wheat and oats, green (see figs. 27 and 28); (2) on panchromatic-25A photos, rusted oats would be expected to photograph very light in tone, rusted wheat moderately light, and healthy wheat and oats, relatively dark (see fig. 29); and (3) on infrared-89A photos, both rusted wheat and rusted oats would be expected to photograph quite dark in tone relative to healthy plants (see fig. 30). Similar results would be expected on oblique aerial photos (figs. 24 to 26) except for slight modifications caused by increased prominence of the wheat and oats inflorescences in oblique views. In all the ensuing photographs taken on September 24, results are in remarkably close agreement with these predictions.

deep, over the entire area, which is in close agreement with the situation depicted in figure 22. In the oblique view (such as the bottom half of figure 24), most of the spore-covered ground is obscured by intervening foliage, whereas in the vertical view (such as the bottom half of figure 27), much of this ground is visible. In addition, the red of the rusted leaves is more conspicuous and the yellowish-green of the maturing wheat heads is less conspicuous in the vertical view than in the oblique.

3. In general, heavily rusted wheat plots were readily detectable on infrared-89A photography because of their relatively dark photographic tones. However, this detection proved more difficult on oblique photos taken with the camera looking away from the sun (fig. 25) than on either vertical photos (fig. 30) or oblique photos taken into the sun (fig. 26).

4. In general, heavily rusted wheat plots were not readily detectable on panchromatic-25A photography, although in some instances they exhibited a somewhat lighter tone than did adjacent, healthy wheat plots.

5. Heavily rusted wheat plots were readily detectable on aerial ektachrome photography, either vertical or oblique (figs. 24, 27, and 28), provided the photographs were taken at sufficiently low altitudes so that color contrast reduction by atmospheric haze was not a serious factor. At progressively higher altitudes, however, the heavily rusted wheat plots became progressively less detectable on ektachrome photography (fig. 28).

6. In addition to determining whether or not rusted areas were detectable, efforts were made to determine the extent to which the actual *severity* of the disease could be estimated on various types of photographs. The results obtained in all such tests are exemplified by a close study of block IV of the 1953 nursery. In block IV, the same 17 varieties of wheat used in blocks I and II were replicated four times by means of 68 sowings, each 4 x 6 feet in size. Because of the random arrangement of these varieties in each replication, the photo interpreter had no preconceived estimate of the rust severity in any one of the 68 rectangles. Under these conditions it was found possible, by using the top stereogram of figure 28, for a photo interpreter (who had been given some indoctrination and field training in the estimation of rust severity) to assess the severity of rust in a 4-by-6-foot rectangle with an average error of less than 10 per cent. This figure was arrived at by comparing the interpreter's estimates with independent ground estimates made by an expert agronomist and based on the proportion of leaf and stem area covered by the pustules of the pathogen. It should be emphasized, however, that this degree of accuracy was not attainable with any other film-filter-scale combination illustrated in this publication. Specifically: (a) on the smaller scales of color photography shown in figure 28 there was too much reduction in color contrast due to atmospheric haze to permit accurate interpretations; (b) on infrared photography there were insufficient tone gradations, regardless of photographic scale (see fig. 30), so that although this photography was excellent for distinguishing heavily diseased from healthy areas, it was of little value in assessing actual severity in intermediate cases; and (c) on panchromatic-25A photographs, consistent with predictions, it was very difficult even to differentiate diseased from healthy plots (fig. 29).



Fig. 24. Aerial ektachrome photos of a cereal crop nursery at University Farm, Davis, California. Annotations in the top photo indicate varieties of wheat sown in Blocks I, II, and VI. At the time the top photo was taken, wheat rust could be found only in trace amounts even with careful study on the ground. When the bottom photo was taken, 23 days later, rust severity (based on per cent of leaf and stem area covered by rust pustules) had climbed to the values indicated by the annotations. Tables 2 and 3, Appendix B, show the chronological development of rust on each variety of wheat in each block labeled in the top photo.

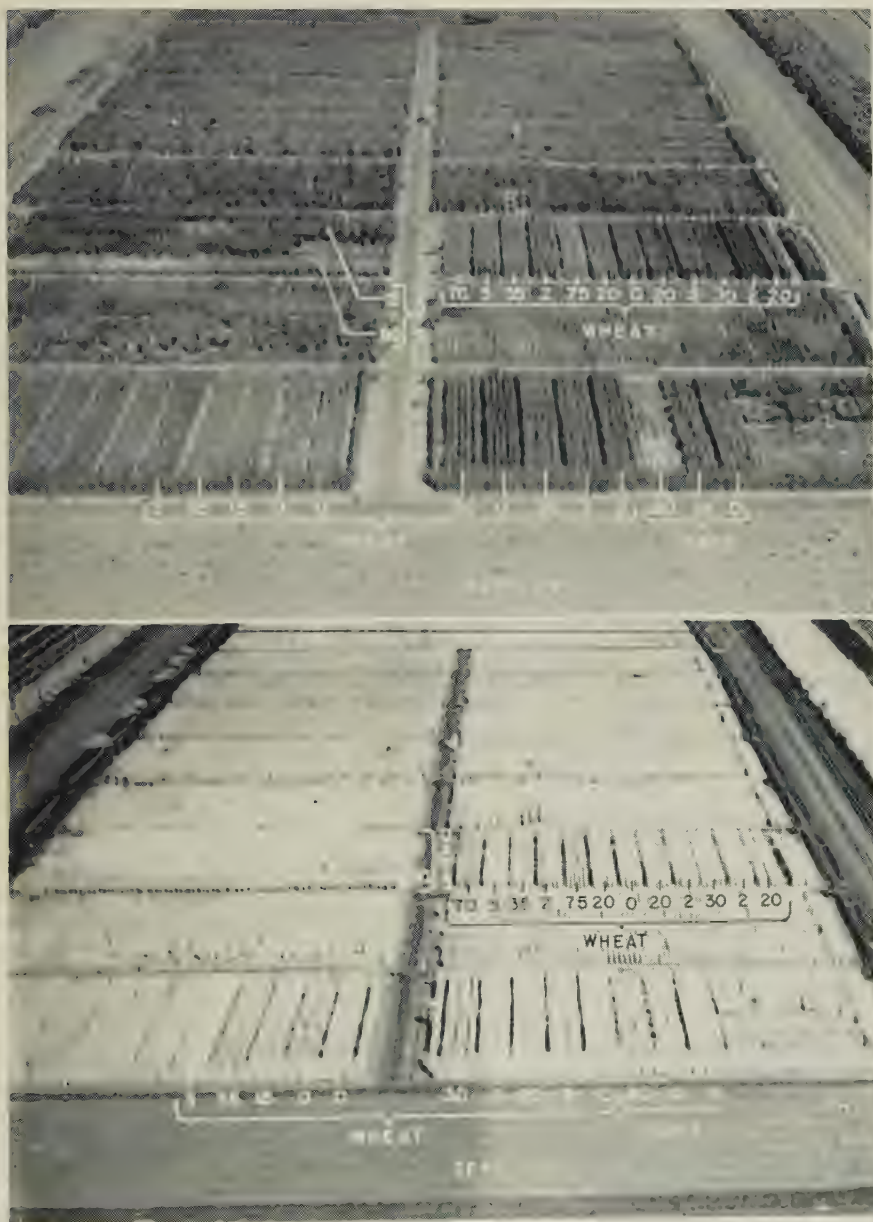


Fig. 25. Oblique aerial views looking north on the same area as shown in figure 24. The top photo (panchromatic-25A), shows a very light tone for oats rust, a moderately light tone for wheat rust, and a relatively dark tone for healthy oats and wheat, as predicted from the spectrophotometric curves. The bottom photo (infrared-89A) shows only a slight darkening of tone due to rust, probably because of the high reflectance from early maturing heads in the diseased plots. This is confirmed by the vertical views (figs. 27-29), on which heads exert less influence.

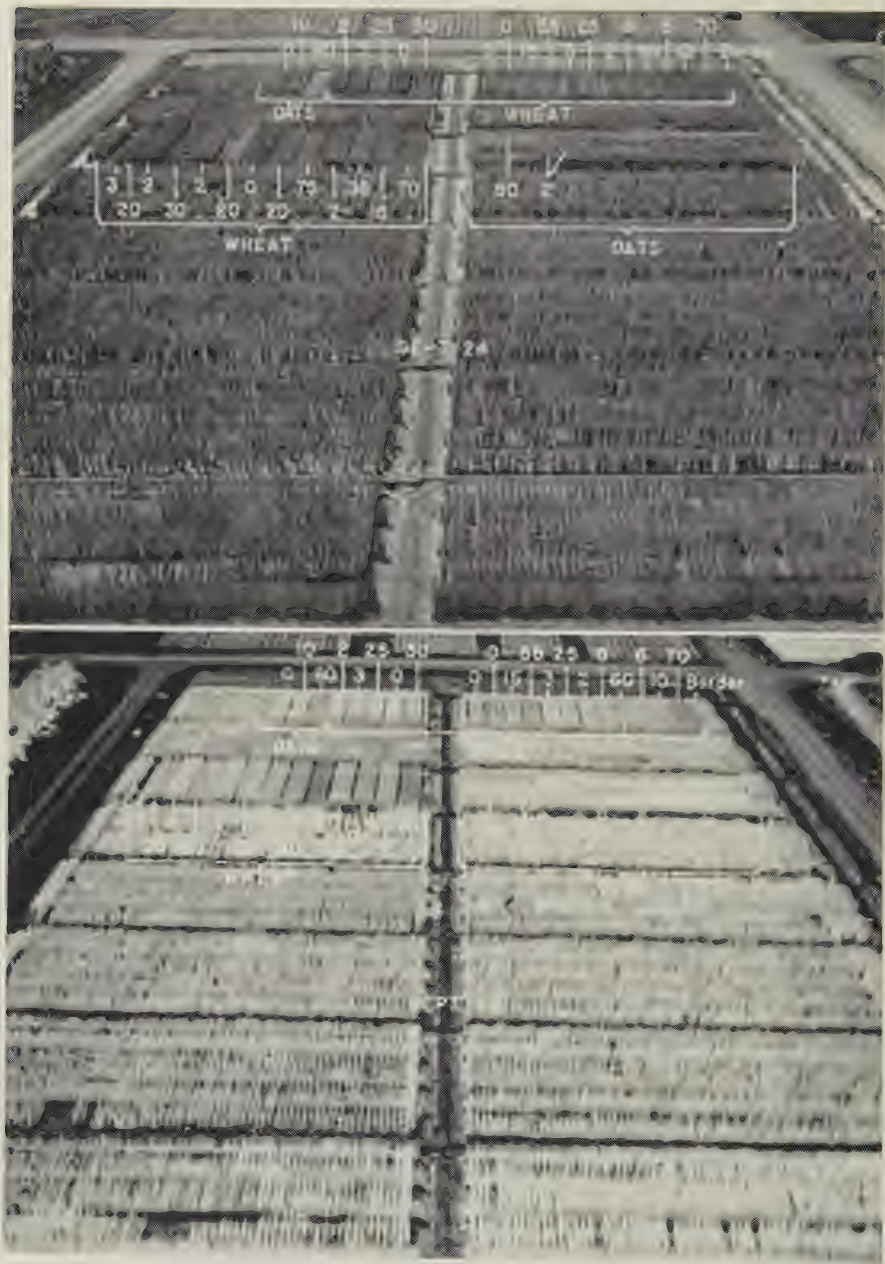


Fig. 26. Oblique aerial views looking south on the same area as shown in figures 24 and 25. Top: Pan-25A photo on which oats rust appears light in tone, but wheat rust does not. One relatively healthy block of wheat (labeled "20") also appears so light in tone as to be confused with wheat rust on this photograph. This is because of the high reflectance of rusting heads which had blown over, as shown in figure 27 (top). On the bottom photo (infrared film), all heavily diseased wheat and oats appear dark in tone, while all healthy wheat and oats appear light.

7. On large-scale ektachrome aerial photographs the prevalence of disease is so readily assessed as to indicate occasional errors or needed refinements in the estimates of rust severity made by an experienced agronomist on the ground. Reference to the bottom photo of figure 27 will illustrate this point in at least two instances. The encircled area labeled "A" obviously has a rust severity of approximately 60 per cent rather than the 30 per cent indicated for this entire plot. The encircled area labeled "B" also has a rust severity of approximately 60 per cent, as labeled, but the remainder of the plot has a much lower severity. In both cases, prompt ground checking showed the situation to be exactly as depicted on the photographs. Following detailed examination of photos such as figure 27, some research agronomists have shown interest in using aerial photos as the most effective means of recording and portraying the results of their nursery plot studies on crop diseases. For example, voluminous tables and graphs would be required to portray the situation which has been faithfully recorded in figure 27 in 1/100th of a second. More commonly, however, aerial photos, tables, and graphs of a test area such as the one in figure 27 should be considered complementary, rather than competitive.

8. A few minutes after the aerial photographs had been taken on September 24, the writer again flew over this nursery area in a helicopter, at altitudes of from 50 to several thousand feet, and examined it carefully both with the naked eye and through various filters, including the ones used in taking the photographs. The objective of this flight was to determine whether the prevalence of cereal crop diseases could be assessed adequately by mere visual aerial reconnaissance without taking photographs. As might have been predicted, the filters were of little or no value in visual reconnaissance, chiefly because they diminished the light intensity to the point where features on the ground were very difficult to distinguish. This was obviously of greater consequence when viewing the nursery through the deep red (89A) filter than when viewing it through lighter filters. Direct visual reconnaissance without filters revealed the scene essentially as it had been depicted on the ektachrome aerial photos, the main difference being that visual reconnaissance gave only a fleeting impression of the situation, while aerial photo reconnaissance provided a permanent record in very great detail. In addition, features discernible only on infrared aerial photography obviously could not be discerned from the air by the naked eye, as the term "infrared" implies.

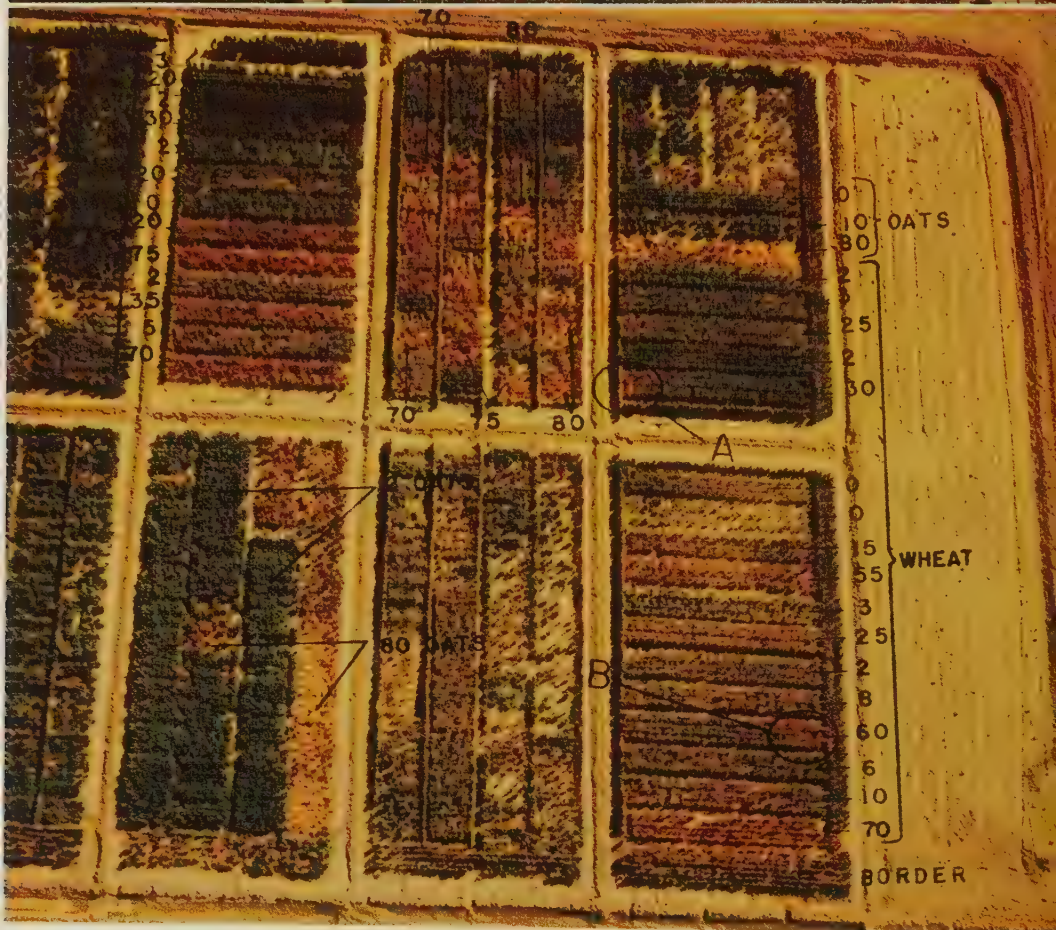
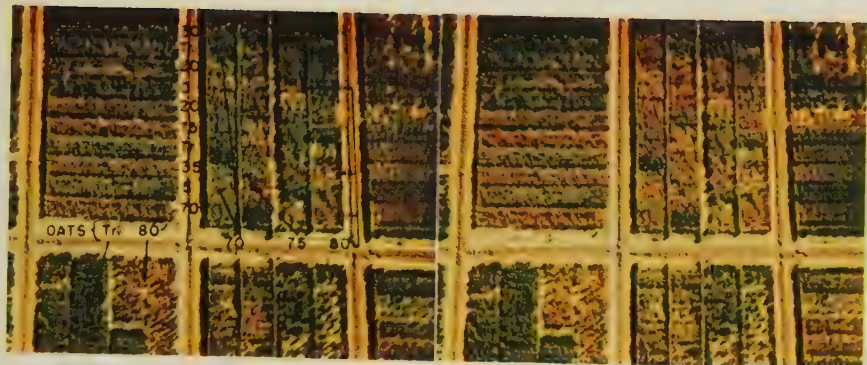
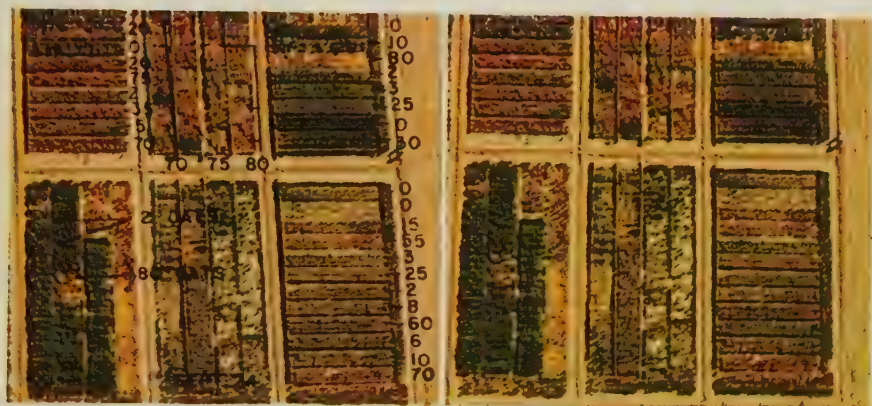


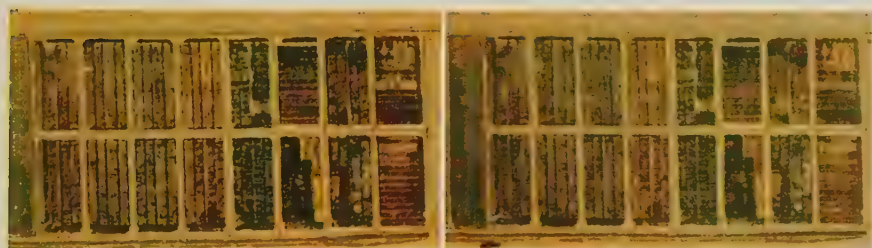
Fig. 27. Aerial ektachrome photos taken on September 24. Top: Oblique view looking south on the Davis nursery (compare with fig. 26). Bottom: vertical view of the same area from a flight altitude of 400 feet. Note (1) the ease of differentiating between oats rust (yellow) and wheat rust (red); (2) the close correlation between wheat rust severity percentages annotated here, which were determined on the ground by an experienced agronomist, and degree of redness of the corresponding wheat plots; and (3) the readiness with which local concentrations of wheat rust can be detected at "A" and "B."



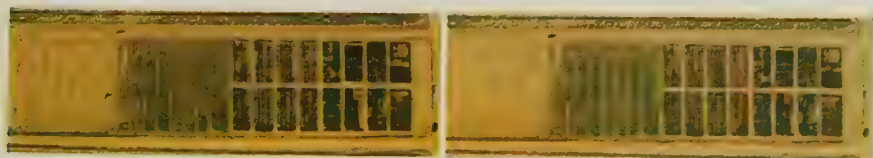
Flight altitude 600 feet.



Flight altitude 800 feet



Flight altitude 2,000 feet

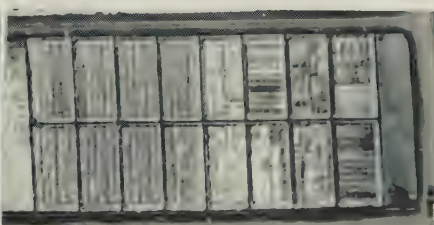
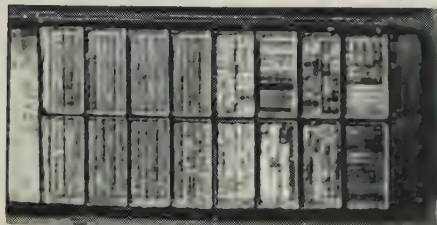


Flight altitude 4,000 feet.

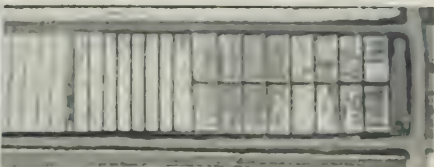
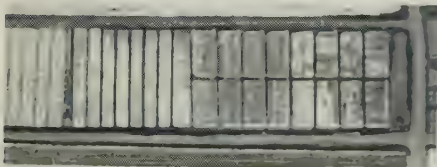
Fig. 28. Aerial ektachrome vertical stereograms of the Davis nursery taken September 24 from progressively higher flight altitudes. The reduction in color contrast at higher altitudes is due mainly to haze interference for short wave lengths as shown in figure 23C. Nevertheless, rust infection is detectable in color photos taken at 10,000 feet (fig. 31). See text for discussion of the 4x6-foot plots in Block IV, the center block of the top stereogram.



Flight altitude 400 feet



Flight altitude 2,000 feet



Flight altitude 4,000 feet



Flight altitude 10,000 feet

Fig. 30. Infrared-89A vertical photos of the Davis nursery taken September 24 from progressively higher altitudes. Note that both oats rust and wheat rust appear dark in tone. Also note very little reduction in tone contrast due to haze as altitude is increased.

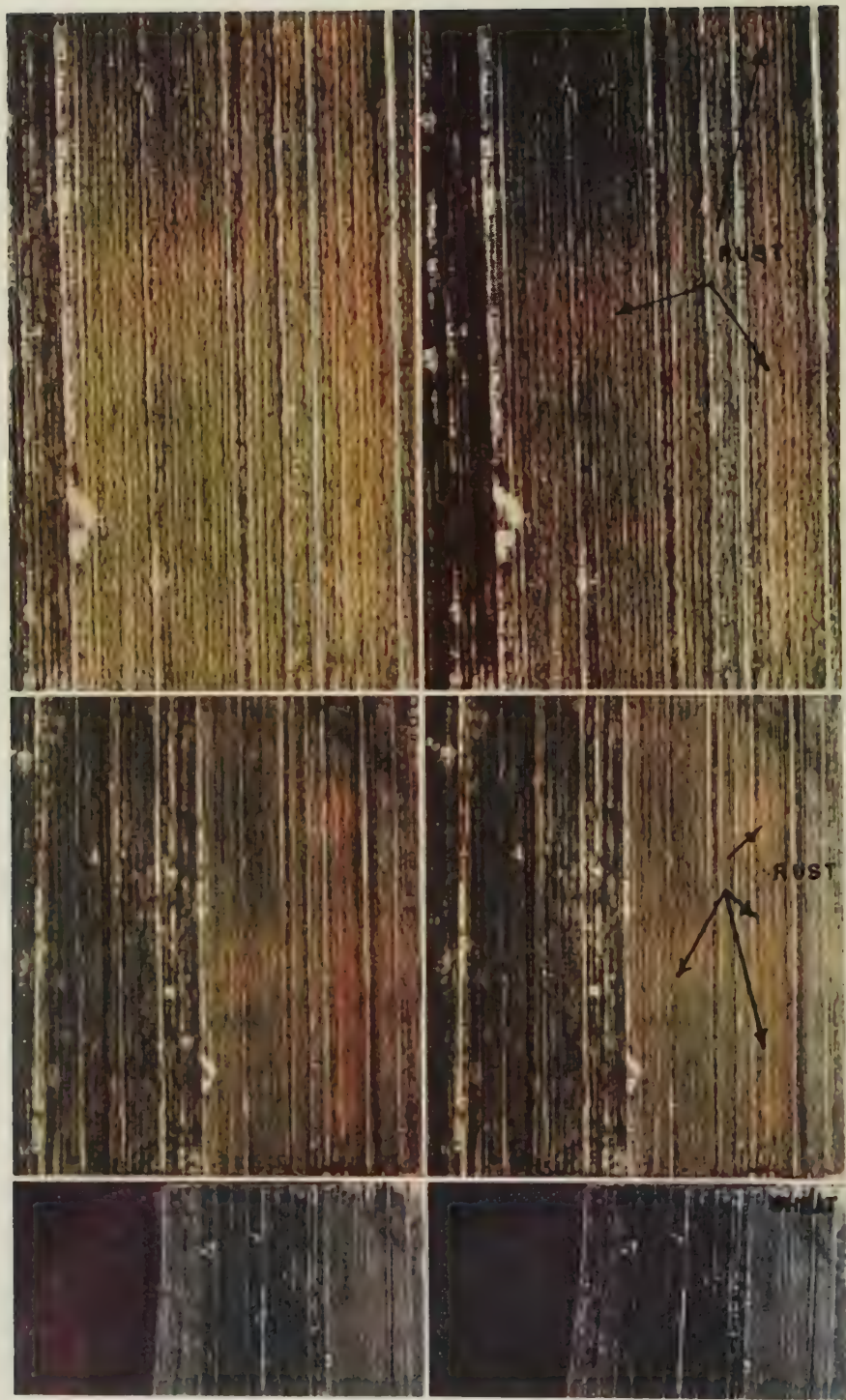


Fig. 1. Aerial ektachrome vertical stereograms taken from flight altitudes of (top to bottom) 0, 4,000, and 10,000 feet, showing natural occurrences of rust in an open field of wheat.



Fig. 32. Aerial ektachrome stereogram of the Davis nursery, taken after most of the cereal crops had matured. By comparison with figures 27 and 28, note increased difficulty of estimating rust severity and yield reduction at this late date.

Photo Interpretation of Yellow Dwarf Virus Disease on Oats and Barley

Other than rusts, the only disease of major concern which infests cereal crops in the Davis area is caused by yellow dwarf virus (Oswald and Houston, 1953). Limited tests were conducted to determine the extent to which this disease might be confused with rust on aerial photographs of cereal crops.

The appearance of oats and barley, in both the healthy state and when infested with the yellow dwarf virus, is indicated in figures 33, 34, and 35. The major results indicated by these photographs and others are as follows:

1. Yellow dwarf virus disease causes a reduction in the reflectivity of infrared light from cereal leaves similar to that caused by rust. The mere presence of dark-toned areas in a field of grain, therefore, is by no means the indicator for some specific disease. In fact, the writer has found instances in which even nonparasitic diseases have caused a similar photographic effect. On the other hand, a uniformly light-toned appearance of grain fields on

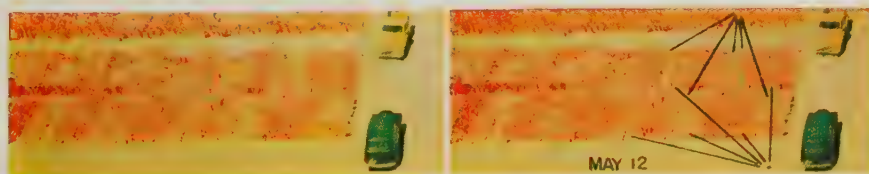


Fig. 33. Oblique stereogram, taken with camouflage-detection film, of a nursery area infested with yellow dwarf virus disease. Lines from the top and bottom of the photo indicate barley and oats plots, respectively, which are disease-infested and which therefore appear brown. Healthy plants in adjacent plots still have high infrared reflectance and therefore photograph red on this film (compare with fig. 34).

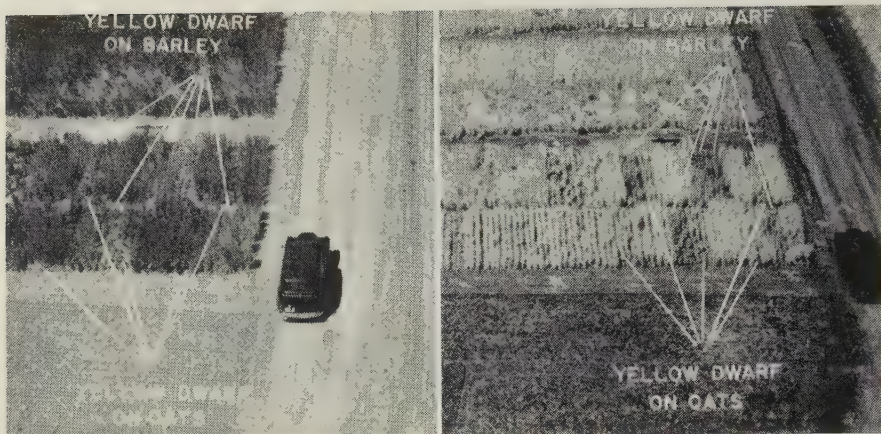


Fig. 34. Aerial oblique photos taken with Pan-25A (left) and infrared-89A, showing the incidence of yellow dwarf virus disease on oats and barley. On the infrared-89A photo, note high correlation between darkness of tone and incidence of disease.

infrared photographs indicated, in all these tests, a uniformly high vigor of the plants.

2. Once dark-toned areas have been detected on small-scale, infrared photos of a given grain field, larger scale aerial photographs of these specific areas, if taken with the proper film-filter combination, may permit positive identification of the disease. Specifically, yellow dwarf virus disease causes a severe suppression of the heads, or panicles, on oats, whereas black stem rust does not (fig. 35). On panchromatic-minus blue aerial photographs taken at scales of 1/1000 to 1/2000, panicle suppression, if present, is generally discernible.

3. Almost certainly, the potential number of factors which might cause a loss of vigor in cereal crops and a consequent loss of infrared reflectance is so great that there is little prospect that 100 per cent accuracy of disease assessment can be made from photo interpretation without some supplementary ground checking. At this point some agronomists might abandon further consideration of aerial photographs as a useful tool. If so, they would be ignoring the fact that, in virtually all current scientific usage of aerial photography, this same limitation applies, yet the photos are used despite such a limitation. Viewing the matter more realistically, it would seem proper to recognize fully both the advantages and the limitations of aerial photos in determining the prevalence of cereal crop diseases, and to determine in each specific case whether the field work eliminated is sufficiently great to justify the expense of using the photos for whatever they are worth. If aerial photos do nothing more than eliminate from further ground study areas which are obviously healthy, they may reduce by 95 per cent or more the area that might otherwise have to be searched.



Fig. 35. Stereograms showing means by which yellow dwarf virus disease on oats can be differentiated from black stem rust on oats through differences in panicle ("head") suppression. In the top photo the panicles are very sparse in the Coast Black Oats (middle plot) which is heavily infested with yellow dwarf virus, as compared with the healthy oats to its right. In the case of black stem rust, however (bottom photo), the panicles appear quite dense in *all* oats bundles and plots, including several which are heavily infested with black stem rust and in which the kernels therefore have failed to develop. This distinction usually can be made on aerial photos taken from flight altitudes up to 2,000 feet, but the aerial photo differences are too subtle to illustrate in this publication.

SUMMARY

Under sponsorship of the National Research Council's Committee on Plant and Crop Ecology an investigation was made of the possibilities for identifying certain healthy and diseased cereal crops from aerial photographs. The principal crops studied were wheat, oats, barley, and rye; the principal diseases studied were black stem rust and yellow dwarf virus disease.

After preliminary tests had been conducted at Stillwater, Oklahoma, and at Langdon, North Dakota, test crops were grown at the University of California's Davis campus. In one series of tests, several varieties of wheat, oats, and barley, varying in their susceptibilities to disease, were grown side-by-side in test plots, artificially inoculated with disease, and carefully cultured

throughout their growth period in order to produce maximum expression of the disease. Periodic records were made of the severity of the disease, expressed in terms of the total leaf and stem area of the host plants covered by the sori or pustules of the pathogen. These periodic determinations, made on the ground by an experienced agronomist, were used as a basis for assessing the accuracy of disease-severity estimates made by photo interpreters. The photo interpreters were supplied with aerial photographs of the test plots, taken periodically throughout the growing season. In a second series of tests, attempts were made to detect the incidence of disease in open fields where cereal crops were being grown and where the disease pathogen entered the area by means of spore showers or other natural means.

With a recording spectrophotometer, measurements of spectral reflectance were made for healthy and diseased crops. On the basis of these measurements, the following four film-filter combinations were selected as offering the greatest promise for providing unique tone or color characteristics for the various crops and diseases to be identified: (1) panchromatic film with a 25A (light red) filter; (2) infrared film with an 89A (deep red) filter; (3) aerial Ektachrome film with the appropriate color-balancing filter; and (4) camouflage-detection film with a "G" (light orange) filter.

Aerial Photographic Specifications for the Photo Identification of Various Cereal Crops and Their Diseases

1. CAMERA: K-17 or equivalent.
2. FOCAL LENGTH: 6-inch preferred for black-and-white photography to provide ample relief exaggeration; 12-inch preferred for color photography to give uniform exposure from center to edge of photograph.
3. FILM-FILTER COMBINATIONS: A. panchromatic film with 25A filter; B. infrared film with 89A filter; C. color film (Aerial Ektachrome) with color-correction filter.
4. ANGLES OF PHOTOGRAPHY: Vertical preferred, with 60 per cent forward lap. Low-altitude, oblique photos frequently are useful also.
5. TIMES OF PHOTOGRAPHY: A. approximately one week after first heading of cereal crops; B. approximately three weeks after first heading of cereal crops (photographs taken during the period when crops are ripe enough for harvest also may be quite helpful).

NOTE: All photographs should be taken within two hours of local noon, if possible, because of the critical nature of tone and color values.

6. SCALES OF PHOTOGRAPHY:

- A. 1/10,000 to 1/20,000 basic coverage, for detecting tone differences.
- B. Approximately 1/4000 spot coverage for detecting lodged grain.
- C. Approximately 1/2000 spot coverage for detecting panicle suppression.

NOTE: Scales as large as 1/500 to 1/1000 of selected spots may be required when attempting accurate estimates of disease severity and yield reduction.

Approximately 40 photographic missions, involving nearly 20,000 exposures, were flown in support of this project by military personnel based at the Naval Air Station, Oakland, California. Fixed-wing aircraft (SNB-5P, Beechcraft) were used for photographs taken at altitudes of 2,000 to 10,000 feet; rotary-wing aircraft (HTE-2 Hiller helicopters and HUP-2

Piasecki helicopters) were used for photographs taken at altitudes of less than 2,000 feet. Photo interpretations were made primarily by the author, with some assistance and verification being provided by personnel of the Navy Photo Interpretation Center, Washington, D.C., and Navy Photo Squadron VPP-876, Oakland, California.

Results of these tests indicate that, on aerial photographs taken to proper specifications and at the proper seasonal state of development of the host plant and pathogen, it is possible for a photo interpreter to recognize (1) healthy wheat, oats, barley, and rye; (2) diseased wheat infested with black stem rust (*Puccinia graminis tritici*); (3) diseased oats infested with black stem rust (*P. graminis avenae*); and (4) diseased oats infested with yellow dwarf virus (Oswald and Houston, 1953). In some instances the photo interpreter, using only small-scale, black-and-white photographs, can detect disease infection centers early enough to permit effective control measures. Frequently, using large-scale, color photographs, he can also estimate disease severity and subsequent yield reduction quite accurately.

In an attempt to systematize the pertinent findings from this study, a dichotomous key is presented below. The key is intended for use by a photo interpreter in keying out the various diseased and healthy cereal crops from his study of their photo image characteristics (Colwell, 1953), much as a botanist or zoölogist might key out a plant or animal from characteristics which he sees with the naked eye or, occasionally, with the aid of a hand lens. The key assumes that the aerial photographic coverage with which the interpreter will be working is at a scale of 1/2000 to 1/4000, with spot coverage at still larger scales. It further assumes that the first three of the four film-filter combinations mentioned above are used and that the photos are taken at two critical periods: (1) shortly after first heading of the host plants, and (2) three or four weeks later, at the time the crops are maturing.

Experience has shown that people have little difficulty in distinguishing vegetable matter (plant life) on aerial photos of the scales here employed. Based on this premise, the key begins with the population known as plant life and, by a brief, dichotomous type of elimination process, progressively narrows the field so that next, only cultivated crops are left; then, of those, only continuous covercrops are left; then, only wheat, oats, barley, and rye. At this point in the key, healthy crops are separated from diseased ones, and the key concludes with an attempt to tabulate the recognition features of the three most important diseases studied, namely, black stem rust on wheat, black stem rust on oats, and yellow dwarf virus on oats.

It is, of course, recognized that the key would have to be modified in certain respects in order to be applicable to some other area. Also, it should be emphasized that certain features are not so invariable as the word descriptions would seem to imply. Nevertheless, it is believed that the key will constitute a useful summary of this work. With this objective in mind, frequent reference is made throughout the key to certain of the foregoing photographic illustrations.

Dichotomous Key for the Aerial Photo Identification of Healthy and Diseased Cereal Crops Growing on or Near University Farm, Davis, California

- A. Man-made cultivation pattern discernible (agricultural crops) See B
- A. Man-made cultivation pattern not discernible (wildland crops,
such as grass and timber) *
- B. Crops forming continuous cover, with individual rows blending
together See C
- B. Crops not forming continuous cover, individual rows usually discernible
(orchards, vineyards, and truck crops, including corn and beans) *
- C. Levees present, following contour of the land (rice) *
- C. Levees absent See D
- D. Crops casting conspicuous shadow on edge of field away from sun . . See E
- D. Crops not casting conspicuous shadow (alfalfa) *
- E. Plants light in tone on infrared-89A photography (healthy cereal
crops) See F
- E. Plants dark in tone on infrared-89A photography (diseased cereal
crops) See I
- F. Plants yellowish-green maturing early and forming mottled, yellow-
green patches (see fig. 6) *healthy barley*
- F. Plants decidedly bluish-green, particularly in the oblique aerial
view (see fig. 7, top) *healthy rye*
- F. Plants a normal bright green, relatively slow in maturing (healthy
oats and wheat; see fig. 7, top) See G
- G. Plants turning brown in vertical view and bright gold in oblique
view when approaching maturity (see fig. 3, D and E) *healthy oats*
- G. Plants turning brown in both vertical and oblique views when
approaching maturity, usually the last crop to lose its green colo-
ration (see figs. 3C and 4) *healthy wheat*
- H. Plants reddish-brown on color photographs, but same tone as
healthy plants on Pan-25A photographs (see figs. 27 and 29) . *rusted wheat*
- H. Plants yellowish on color photographs, light in tone on Pan-25A
photographs (see figs. 27 and 29) See I
- I. Panicle suppression discernible on aerial photos at scales of
1/2000 or larger (see fig. 35) *yellow dwarf virus on oats*
- I. Panicle suppression not discernible *rusted oats*

* Keys completed or in process of preparation, but omitted here as they are not essential to this study.

CONCLUSIONS

Results of this investigation point to the following conclusions: (1) On aerial photographs taken to proper specifications and at a proper seasonal state of development of the host plant and pathogen it is possible for a photo interpreter to identify (a) healthy wheat, oats, barley, and rye; (b) diseased wheat infested with black stem rust (*Puccinia graminis tritici*); (c) diseased oats infested with black stem rust (*P. graminis avenae*); and (d) diseased oats infested with yellow dwarf virus (Oswald and Houston, 1953). (2) In many instances, not only the presence of disease infection centers, but also the severity of disease occurring in the infested plants can be estimated with a high degree of accuracy from aerial photographs. While no cereal crop diseases other than the above were studied in detail, it is probable that, under certain conditions, the grain fields would contain other diseases, including nonparasitic ones, which a photo interpreter might confuse with the ones here studied. As in all types of photo interpretation, frequent ground checks should be made when possible to verify the accuracy of the interpretations. (3) Very shortly after the spore of a rust-producing fungus germinates on a healthy grain leaf, fungal hyphae develop which invade and plug up the spongy mesophyll of the host plant. This sharply reduces the infrared reflectivity from leaves of the infested plant even before the leaves become visibly discolored by the disease. Consequently, disease infection centers may first be detectable as dark-toned areas on infrared aerial photographs. However, it should be emphasized that certain other conditions, including the presence of standing water in grain fields or the lack of a uniformly high density of plants, may also cause portions of a grain field to appear dark in tone on infrared aerial photographs. Where such conditions are likely to occur, it may be necessary either to obtain large-scale photographs of the dark-toned areas, or actually to visit these areas on the ground to determine which of the dark-toned areas are diseased. In such cases, infrared photography on a small scale still would be of considerable value by permitting all light-toned (healthy) grain fields to be excluded from more detailed study. In most of the situations encountered in the Davis tests this step alone would have narrowed the search for disease infection centers to less than 5 per cent of the area that otherwise would have had to be searched. (4) According to the statements of expert pathologists and agronomists, the early detection and treatment of these infection centers would, under certain conditions, permit economic control of the disease before it could reach epiphytotic proportions.

APPENDIX A

Aerial Photographic Equipment and Techniques

Many of the aerial photographs in this project were taken from fixed-wing aircraft, at altitudes ranging from 2,000 to 10,000 feet above sea level, with the equipment illustrated in figure 36. Both the equipment and methods used were conventional, and are fully described in the *Manual of Photogrammetry* (American Society of Photogrammetry, 1952) and elsewhere. One particu-

larly important technique was that of obtaining all vertical photographs with the stereo base aligned in a uniform direction and with a uniform overlap of 60 per cent between successive exposures. This permitted the mounting of all vertical stereograms to a uniform orientation, parallel to the flight line. It also enabled the photo interpreter to determine the extent to which conventional stereoscopic parallax might facilitate his interpretation of cereal crops and their diseases from various flight altitudes.

In obtaining the very large scale (1/400), vertical photographs at Stillwater, Oklahoma, a special aerial camera known as the "Somme continuous stereo strip camera" was employed. In this camera the film moves continuously at a rate commensurate with the rate of movement of the image at the camera's focal plane. This serves to "freeze" the image of an object to one particular portion of the film during the period that it is being photographed. Had this low-altitude (less than 200 feet) photography been attempted with a conventional aerial camera, excessive blur due to image motion during the exposure would have resulted because of the following combination of conditions: (1) relatively slow speed of the film (exposure index of 40); (2) relatively high speed of the aircraft (the plane used was an F-2H5P "Ban-shee" jet photographic plane having a flying speed of approximately 400 miles per hour); and (3) relatively large scale of the photographic image with consequent high rate of travel of the image at the camera's focal plane.

It was recognized early in the project that certain kinds of information relative to the cereal crops and their diseases could best be illustrated by means of low-altitude, stereoscopic photography, either vertical or oblique. When attempting to obtain such photographs from fixed-wing aircraft, it was found that their relatively high rate of travel and limited maneuverability posed serious problems in (1) framing the target properly; (2) photographing it from the correct camera stations; (3) minimizing image blur; and (4) obtaining sufficient overlap to permit stereoscopic viewing of the photo images. Each of these problems was satisfactorily overcome when a helicopter was used (figs. 37 through 40).

Since one important aspect of this study was to determine the photographic film-filter combination best suited to the assessment of cereal crop diseases, it was quite important that comparable photographs of the test area be taken with each combination. It was not feasible to make multiple-camera installations in the helicopter; a separate photographic run was required for each film-filter combination. Therefore, such factors as flight altitude, overlap, photographic scale, and degree of obliquity of the camera had to be carefully controlled on successive runs over the target if valid comparisons were to be made among the various film-filter combinations being tested. Furthermore, it was important that, on successive dates during the development of each disease, comparable photographs be obtained with regard to each of the above factors. The extent to which use of a helicopter permitted the photographer to fulfill these many requirements is indicated by the various large-scale aerial photographs in this paper.

The helicopter was of great value in taking the photographs because: (1) Ability to make right-angle turns enabled the photographer to take oblique photographs of a rectangular test area from all four sides in one continuous

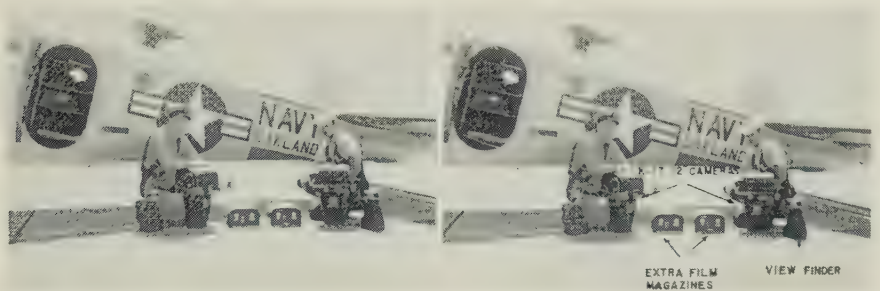


Fig. 36. Stereogram showing fixed-wing aircraft (SNB-5P) and camera equipment used in taking high-altitude, vertical photos at Davis.



Fig. 37. Stereograms showing rotary-winged aircraft and camera equipment used in taking low-altitude, vertical and oblique photos at Davis. Top two show two Hiller helicopters (Model HTE-2) operating from the University Airport at Davis. The bottom stereogram shows a twin rotor Piasecki (Model HUP-2) in which the photographer is taking motion pictures of the nursery area for use in a training film on photo interpretation.

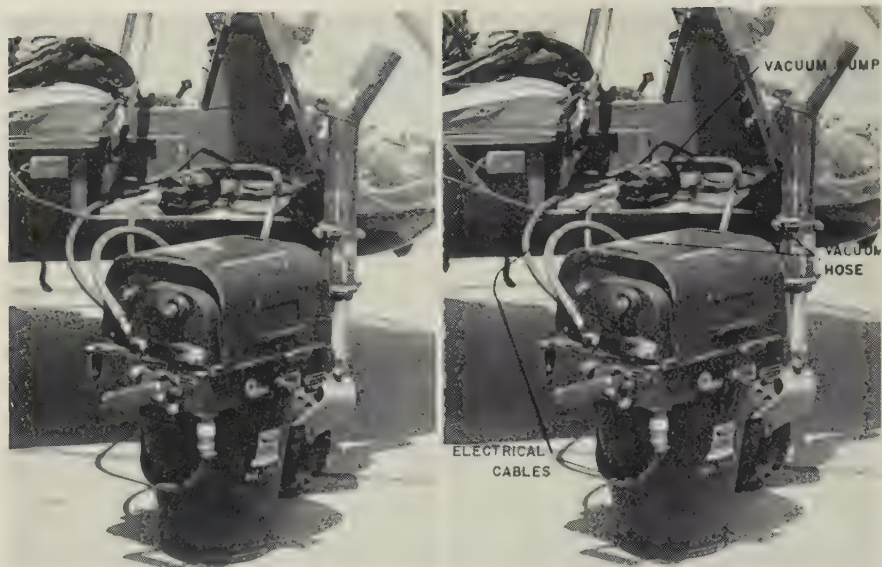


Fig. 38. Stereogram showing the K-17 12" camera installation in a Hiller (HTE-2) helicopter. Note 24-volt electrical leads for recycling camera. Also note manner of installation of a special vacuum pump which proved necessary for sucking the film flat against the camera platen at the instant of photography, in order to keep all parts of it in sharp focus.

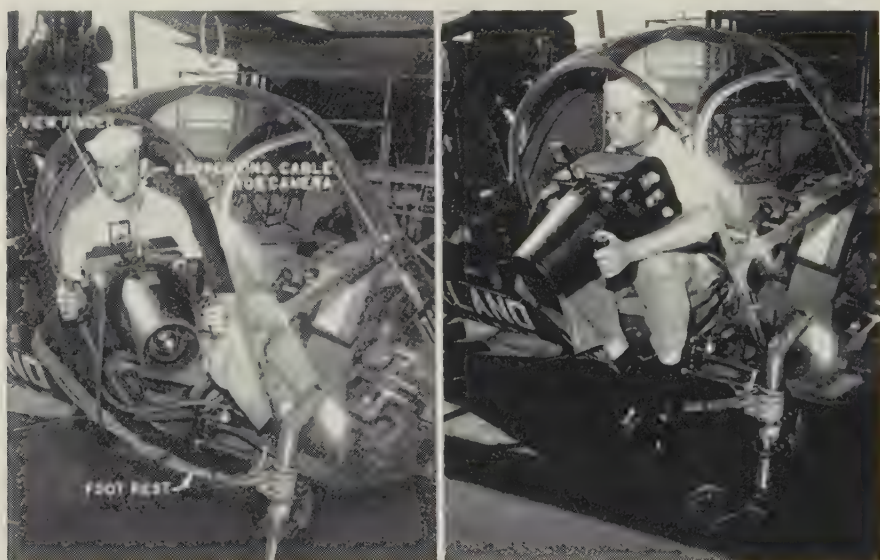


Fig. 39. Manipulation of the K-17 12" camera by a photographer in the HTE-2 helicopter. Left photo shows a cable suspended from the airframe, used to support the camera except when photos were actually being taken. This proved necessary because of the excessive weight of the camera, the rather precarious perch of the photographer, and the occasional instability of the helicopter. Right photo shows how photographer used improvised foot rest (a rope sling) to help him support entire weight of camera at instant of exposure (note slack in supporting cable). Aircraft vibrations, rather than being transmitted to the camera, were thus largely absorbed by photographer. This resulted in sharper photographic images.

circuit. (This was done to determine the best angle, with respect to the sun, for detecting diseased areas.) (2) Ability to reduce forward speed while the camera was being recycled shortened the interval between exposures. As a result, the prints could be viewed stereoscopically in spite of the camera's nearness to the area photographed. (3) Altitude could be accurately controlled because of the helicopter's ability to climb and descend vertically in small increments. (4) Changing of film magazines was facilitated by being able to land and take off from the road beside the test plots—an important feature, since it was not feasible to make multiple camera installations on the helicopter. (5) Visibility was excellent for both pilot and photographer, with relative freedom from aircraft obstructions when taking oblique and vertical photos. As a result of these factors, it was possible to obtain, in less than one hour, all the photo coverage required on one particular date for a given test area. Had an appreciably longer period of time been required, variations in sun altitude and light intensity would have been sufficiently great to invalidate comparisons of photos taken with the various film-filter combinations.

Two types of helicopters were employed in these tests: (1) the Hiller, Model HTE-2, having a single main rotor assembly (fig. 37); and (2) the Piasecki, Model HUP-2, having two main rotor assemblies (fig. 37). Both types proved satisfactory for the aerial photography, although excessive vibration at times made it difficult to obtain sharp pictures.

The loaded K-17 camera was so heavy that the photographer had difficulty holding it in his hands for long periods of time. Nevertheless, it was considered desirable to obtain photographs taken in this manner in order to minimize image blur resulting from aircraft vibration. Therefore, a flexible supporting cable was used (fig. 39) so that the camera could be suspended from the helicopter frame during each approach run on the target. This permitted the photographer to rest between runs and even during a run except when actually taking pictures. At the instant the picture was taken, however, the camera's weight was not supported by the cable, but entirely by the photographer. (fig. 39).

As shown by the illustrations, either a rope sling or a metal frame was improvised to serve as a footrest for the photographer. Both the pilot and the photographer were equipped with conventional safety belts and with intercommunication equipment. The latter proved to be essential in implementing teamwork during a photographic run. In some instances goggles were required because prolonged exposure of the photographer to the air-stream caused his eyes to water and impaired his vision.

Acceptable photographs were taken by numerous people, including the writer, who had little or no experience in taking photographs from a helicopter. Nevertheless, certain difficulties were encountered when attempting to take photographs of this type:

(1) When flying close to the ground over dry terrain, the strong down-draft of air beneath the helicopter's rotary blades tended to create such a dust storm that it was virtually impossible to take good photographs. For the same reason, some of the images of cereal crops could not be fused stereoscopically because the foliage had been buffeted from one position to another during the interval between exposures, thereby introducing a very distracting artificial parallax. At altitudes of greater than 50 feet, however, neither of these factors proved troublesome.

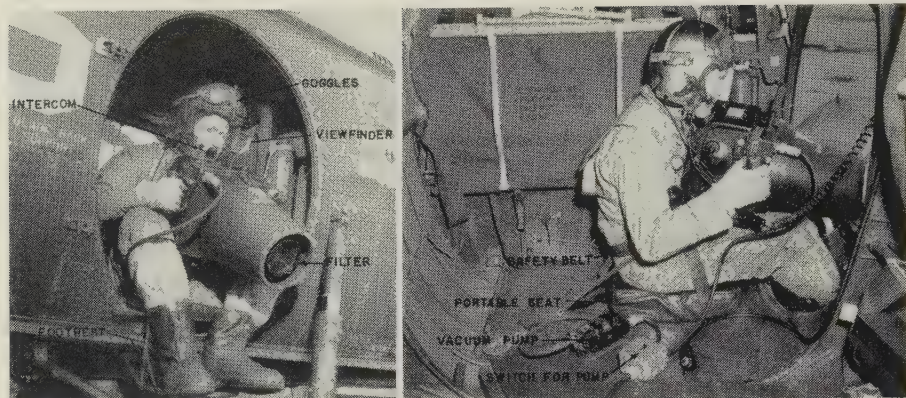


Fig. 40. Two views showing a K-17 camera installation in the HUP-2 helicopter. Note that photographer operates from a hatch in the middle of the aircraft rather than from the copilot's seat. The greater stability of the specially-constructed foot rest shown here permitted photographer to support entire weight of camera between his knees during an entire photographic run. Hence no supporting cable for the camera was needed in this type of helicopter.

(2) Many of the photographs had to be taken at altitudes ranging from 50 to 500 feet. This corresponds closely to the altitudinal range considered most hazardous by helicopter pilots since it is too low to permit any emergency landing by means of autorotation in the event of engine failure and it is too high to permit any beneficial use of the "aircushion" created by the strong downdraft of air from the rotary blades. For these reasons some pilots are unwilling to hover or even to fly at speeds as low as 30 to 40 miles per hour while operating within this altitudinal range. Accordingly, the photographer was sometimes limited as to the types of photographs he could obtain.

(3) With amazingly high frequency the shadow of the helicopter tended to appear within the area to be photographed. Furthermore, because of the relatively low altitudes, the shadow tended to occupy a very large portion of the photo and was therefore much more conspicuous than it would have been on conventional, high-altitude photographs. While this difficulty is by no means insurmountable, the limitations imposed by it should be clearly recognized.

(4) The limited carrying capacity of a small helicopter may limit the flexibility with which a photographic mission can be flown. For example, in photographing the test areas at Davis, it was usually necessary to transport the extra film magazines and several gallons of high-test aviation gasoline from the Oakland airport to the test area by automobile—a distance of 70 miles.

In summary, it may be said that while the helicopter has proved exceedingly valuable as a platform from which to take aerial photographs, its versatility is still limited by its performance characteristics. Although rotary-wing aircraft can perform certain types of photo reconnaissance missions that fixed-wing aircraft cannot, the reverse is also true. Accordingly, the relation between these two types of aircraft, when used for such purposes, should be recognized as complementary rather than competitive.

APPENDIX B

Rust Development and Yield Reduction on Wheat and Oats

Figures 41 and 42 and table 1 show the yield reductions on wheat and oats, caused primarily by rust, in the 1953 nursery tests. As seen in table 1, an important secondary effect for some varieties was stem breakage and consequent premature ripening caused by a high wind on October 2.

Tables 2 and 3 provide a chronology of rust development on Blocks I, II, and VI of the 1953 nursery tests.

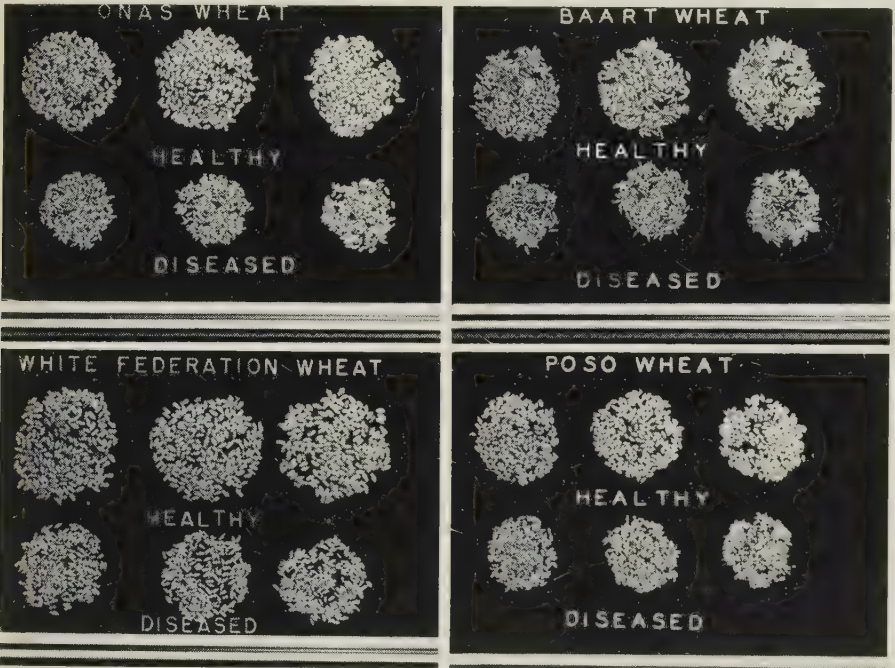


Fig. 41. Effect of black stem rust on yield from 100 grains of wheat from Block VI of Davis nursery. Yield reductions *per acre* were, of course, even greater than this figure would indicate, because fewer wheat grains *per acre* were matured in the rust-infested plots than in the healthy ones. Compare with table 1, Appendix B, and with figure 24.

APPENDIX TABLE 1

EFFECTS OF RUST SEVERITY AND STEM BREAKAGE ON YIELD OF WHEAT AND OATS IN BLOCKS II AND VI

Variety	Rust severity	Stem breakage	Yield depression
	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>
Onas wheat.....	80	90	90
Baart wheat.....	70	60	82
White Fed. wheat.....	85	15	72
Poso wheat.....	75	30	57
Palestine oats*.....	80	100	71

* Crop had essentially matured prior to stem breakage by wind on October 2.



Fig. 42. Effect of black stem rust on yield from 100 grains of oats from Block II of Davis nursery. Compare with table I, Appendix B, and figure 25. Note that the diseased florets, although containing only shriveled oats kernels, are almost as large as the healthy florets. This partially explains the absence of panicle suppression in rusted oats as shown in figure 35.

APPENDIX TABLE 2
CHRONOLOGY OF RUST DEVELOPMENT ON WHEAT AND OATS IN BLOCKS
I AND II*
(Compare with figs. 24 and 27)

Variety (reading from left to right in fig. 24)	Stem rust on successive dates						Heads dry or ripe			Stems broken by wind
	9-8	9-14	9-21	9-24	9-28	10-5	9-21	9-28	10-5	10-2
	per cent†						per cent†			per cent
Ramona wheat.....	2	10	55	70	90	90	0	45	100	2
Ramona 44.....	0	tr.	5	10	30	40	0	2	10	2
Ramona 50.....	0	0	2	6	10	25	0	0-tr.	3	1
Poso wheat.....	tr.	7	45	60	75	75	0	15	85	15
Poso 44.....	0	1	3	8	22	25	0	tr.	7	3
Poso 48.....	0	0	tr.	tr.	1-2	2	0	0	7	5
Big Club wheat.....	tr.	2	5	25	60	75	0	0	80	15
Big Club 43.....	0	0	1	3	7	17	0	0	3	0
White Fed. wheat.....	1	6	40	55	75	80	0	10	98	10
White Fed. 38.....	0	2	5	15	25	30	0	2	30	2
White Fed. 45.....	0	0	0	0	0	tr.	0	0	15	0
White Fed. 50.....	0	0	0	0	0	tr.	0	0	20	0
Onas 49 wheat.....	2	5	28	30	55	70	0	0	80	65
Onas 53 wheat.....	0	0	0	0	0	0	0	0	0	0
Baart wheat.....	tr.	3	18	25	45	70	0	0	90	50
Baart 38.....	0	tr.	1	3	8	30	0	0	35	5
Baart 46.....	0	0	tr.	tr.	tr.	tr.	0	0	tr.	0
Palestine oats.....	6	45	80	80	80	..	50	99	100	..
Sel. 4703† oats.....	tr.	1	3	10	18	18	0	5	25	..
Sel. 4712 oats.....	0	0	0	0	0	0	0	0	tr.	..

* Based on data compiled by Suneson (1953).

† tr. = trace.

‡ Heterozygous population with regard to rust. Only one fourth susceptible.

APPENDIX TABLE 3
CHRONOLOGY OF RUST DEVELOPMENT ON WHEAT IN BLOCK VI
(Compare with figs. 24 and 27)

Variety (reading from left to right in fig. 24)	Stem rust on successive dates						Heads dry or ripe			Stems broken by wind
	9-8	9-14	9-21	9-24	9-28	10-5	9-21	9-28	10-5	10-2
	per cent*						per cent*			per cent
Ramona wheat.....	1	15	65	70	85	85	0	65	100	1
Ramona 50.....	0	tr.	4	5	20	40	0	tr.	30	5
Poso wheat.....	2	5	27	35	75	75	0	5	80	30
Poso 48.....	0	tr.	tr.	tr.	2	2	0	0	5	1
White Fed. wheat.....	3	20	70	75	85	85	0	85	100	15
White Fed. 38.....	tr.	2	15	20	35	35	0	3	45	5
White Fed. 50.....	0	0	0	0	tr.	tr.	0	0	5	0
Baart wheat.....	tr.	2	13	20	55	70	0	0	95	60
Baart 46.....	0	0	0	tr.	1	1	0	0	0	0
Onas 49 wheat.....	tr.	2	15	30	65	80	0	0	98	90
Onas 53.....	0	0	0	tr.	tr.	tr.	0	0	0	0
Big Club† wheat.....	tr.	1	12	20	60	80	0	0	80	10
Big Club 43†.....	0	0	1	3	10	20	0	0	0	0

* tr. = trace.
† Only two rows each.

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